THE

JOURNAL OF GEOLOGY

SEPTEMBER–OCTOBER, 1912

MICROSCOPICAL PETROGRAPHY FROM THE QUANTITATIVE VIEWPOINT

FRED. EUGENE WRIGHT
Carnegie Institution of Washington

INTRODUCTION

The development of petrology has been along the lines of normal growth followed by other sciences. From the Stone age on, people have had to do with rocks and have gathered, in the course of the centuries, a vast amount of information about them, their characteristics, their modes of occurrence, and their uses in practical life. Different rock types have received different names, and, up to the last century, were classified according to their general appearance and the purposes they served. Fine-grained rocks, like phonolites, the component minerals of which could not be distinguished by the unaided eye, were considered homogeneous and grouped with minerals, until chemists were able to show by partial analysis that part of the rock was soluble in acid and part insoluble. With the advent of the petrographic microscope, a new and fascinating world was opened to the student of rocks, and for some decades the interest was centered in the qualitative description of rocks, their mineral composition, and their textures. It was virgin land for the petrologist to explore, and the methods he adopted were the methods of reconnaissance, analogous to those employed by the geologist, who

visits a new country, like Alaska, to obtain a general idea of the geologic lay of the land and the rock types there represented. During this reconnaissance period, petrography, or rock description, was the prominent feature of petrology, as the thick papers of that time testify. Men were interested in rock types and rock classification. They wished to cover the entire field, and to do so had, of necessity, to adopt the methods of reconnaissance. Their methods and their classifications were all essentially qualitative in nature. After this preliminary work came the more detailed investigations, such as are represented in geology by folio and economic work with large-scale base-maps and only limited areas to cover in a given time.

A science must always develop from the qualitative to the quantitative, and the process is necessarily a gradual one. In science the term qualitative is usually applied to statements in which no definite limits to the quantities involved are expressed, while in quantitative statements such limits are definitely set. These limits may vary widely in their order of magnitude and one quantitative statement may be only roughly quantitative (first approximation) while a second may be highly precise. No observations are ever absolutely accurate; the absolute quantitative cannot be attained in the physical world and the idea of limits or degrees of approximation to truth (probable error) pervades all science. Such limits establish at once boundary lines or fences within which speculation must be held. In a qualitative statement such limits are not given, with the result that they may be arbitrarily extended or decreased by the investigator as the exigencies of his case demand. The smaller the limits in quantitative statement the higher the degree of approximation to truth, the fewer the possibilities for misinterpretation, and the greater the probabilities for correct generalization by the scientist. The growth of a science rests, in part at least, on the development of exact methods of attack and on the precise data of measurement accumulated thereby.

The observer who applies only reconnaissance methods to detailed work requiring exact methods is doing an injustice to the work, and is actually wasting his time, because such work has to

be done over later on. A mechanic who attempts to make a fine spirit level or microscope with poor tools cannot produce a good job. A petrologist on detailed work who describes rocks in the way they were described thirty years ago, and uses the microscope as it was then used, is doing an injustice, not only to the reader, but to the microscope and the tools of precision which are now placed at his disposal.

There is a genuine pleasure on the other hand, in making the most out of the tools we have, and in gathering data, the accuracy of which we know definitely and can state in terms which will be intelligible to observers a century hence. In short, it is only by the accumulation of tangible facts, and grouping of such facts by correct generalization, that real progress is made. From a few facts a mind of genius may intuitively infer and state a correct generalization which covers a whole group of facts to be discovered later, but most of us are not in that class, and it is our duty to assemble the facts—facts which are real facts, based on precise data of observation.

Strictly speaking, quantitative work means control over all parts of a given system. The order of accuracy of all measurements made is definitely known and any observer at a later date should be able to repeat the measurements and obtain similar results. The system is, in short, reproducible. Quantitative work is tangible throughout and we know definitely its behavior at all times during our observations. In qualitative work, on the other hand, the system is imperfectly defined, no definite limits are set, and the results, obtained, lack precision; their probable error is unknown and they are indefinite and uncertain to that extent. A strictly quantitative piece of work, the accuracy of which is adequately stated, produces on the observer, and on the reader as well, a feeling of confidence and stability, which qualitative work with its uncertain elements can never produce. A sense of control and mastery over the factors of an intricate system is a natural sequence of good quantitative work and is, psychologically, one of the greatest rewards granted to the student of nature.

There is still another feature which may be emphasized. In

attacking a problem, the different methods employed should be of about the same order of accuracy. It is useless to conclude that because precise methods are used on one part of a problem, the final result will be of the same order of accuracy, no matter what other methods are employed. The different methods should be co-ordinated and the observer should exercise proper judgment in applying his methods. Thus in rough traversing it would be a waste of time to use a theodolite and to read angles to seconds and then to measure the distances by pacing; or, vice versa, to attempt accurate triangulation with a pocket compass even though the base line be most carefully measured. There are cases, on the other hand, where certain mechanical operations, which are complete in themselves, can be readily and accurately performed, as, for example, the weighing of chemical precipitates; in this instance, it would be obviously improper to weigh the precipitate on a rough hand-balance, even though the probable error, resulting from such a procedure, might be within the probable error of the chemical methods employed. The order of accuracy of the final result would be unnecessarily decreased thereby, since its probable error is a direct function of the probable errors of the different steps involved in the process. To apply these principles successfully to actual problems requires critical judgment on the part of the observer.

All of this seems obvious, but it is not always realized in practice. Instruments are used, but their adjustment is rarely tested. Extinction angles are measured to the minute, and so stated, but the observer may fail to test the adjustment of his microscope and the nicols may be out half a degree or more.

The same holds true of the use of quantitative data. From a series of known facts a scientist evolves a theory and then searches for further data to substantiate or disprove his theory. This course of procedure is right, provided he examine critically into the data themselves—how they were obtained, their probable errors, and so forth.

The use of mathematics in this connection is important. Mathematics is a system of highly perfected logic, expressed in the form of symbols, and can be applied to practically all problems

in which the quantitative element enters. It is a highly developed system and impressive to most of us but "Huxley warned us that the perfection of our mathematical mill is no guaranty of the quality of the grist."[1] If we put into our mill loose data with large probable errors we cannot expect our final results to be more than first approximations. The more accurate the initial data the more accurate and satisfactory the final result. A statement cast in mathematical form does not prove that it is correct even though the mathematics be rigidly true. Mathematics, because it is logical and concise, is often used to express, in general form, relations the exact numerical values of which are not definitely known—such values being then represented by appropriate symbols. For purposes of generalization and the framing of a theory by the logical grouping of observed facts into a simple co-ordinated system, mathematics is invaluable because it serves to express in a single sentence the results and essentials of a whole course of reasoning. The more accurate the facts and results thus used, the greater the degree of probability for correct generalization and the easier the process of such generalization. The non-mathematical reader may examine the premises on which any mathematical argument is based and then use his common-sense in testing the conclusions.

Quantitative work requires more time than qualitative work but petrography has now reached a stage where quantitative work is required. To the observer accustomed only to rapid qualitative methods, quantitative methods necessarily seem slow and irksome and not yielding of immediate results, and he may even be tempted to question whether such methods are really worth the while and repay the energy and time which must be put into them. But in petrography the qualitative reconnaissance period has passed and it is no longer permissible in good work to ignore the quantitative element altogether. It is only by the accumulation of precise data that many of the large problems of petrology will be solved, and until then the solutions will remain matters of opinion supported more or less by a slender foundation of fact. Never before has the need for exact evidence, both from the field and

[1] Extract from address by R. S. Woodward, "On the Mathematical Theories of the Earth," *Proc. Amer. Ass. Adv. Sci.*, 1889, p. 62.

from the laboratory, been felt in petrology as it is today. The pioneers have done the reconnaissance work for us and we must proceed along quantitative lines of attack before we can hope to obtain even approximate solutions of the big problems ahead. Each one of us may contribute his share and add his little stone to the structure by adopting the quantitative viewpoint and realizing its importance in his attitude toward science in general and petrology in particular. In petrology *the quality of our quantitative work is far more important than the quantity of our qualitative work.*

Having now considered the standards postulated by modern petrology, our next step will be to show that the present-day tools and methods of microscopical petrography measure up to these requirements and are furthermore easy of application and simple in principle. We base our judgment of the value of a tool or method on its effectiveness, its simplicity, its adjustable sensibility, and its range of applicability. An instrument whose sensibility can be adjusted to meet the different conditions of observation which may arise is obviously superior to an instrument whose sensibility is rigidly fixed and adapted for only one particular set of conditions. The range of applicability as a feature in any instrument should not be carried too far because practical experience has shown clearly that the so-called universal instruments are, as a rule, unsatisfactory and often do not accomplish in a thoroughly competent manner any one of the several purposes for which they are intended. To fulfil a given set of conditions adequately, it is usually necessary that a special instrument be designed for the purpose. Thus, a small caliber rifle may be admirably suited for small game, but for larger game it is wholly inadequate, and may do more harm than service in an emergency; vice versa, a large caliber rifle is of little value for hunting small game.

The first tools which are devised for a given purpose are usually affected by "children's diseases," as Dr. A. L. Day has expressed it, and only by careful mechanical attention can such troubles be eliminated. The instruments and methods of microscopical petrography have in large measure passed through and beyond this stage and have been developed to such an extent that practically all the optical properties of mineral grains can now be

determined easily and without complicated apparatus on favorable plates or grains 0.02 mm. in diameter and over. It may be of interest to indicate briefly a few of the methods which experience has shown to be most satisfactory in actual work.

ADJUSTMENT OF THE PETROGRAPHIC MICROSCOPE

In these methods it is assumed that the microscope is properly adjusted, otherwise the results obtained may be seriously in error. The simplest method for testing the adjustment of the petrographic microscope is probably the following: (1) Remove from the microscope all lenses—ocular, objective, and condenser—and point it directly at the sun whose rays are parallel and so intense that a rotation of less than 1′ of one of the nicols from the position of total extinction is readily discernible. When the nicols are accurately crossed the sun appears as a dim disk in the dark background. (2) Test the adjustment of the cross-hairs of the ocular to the principal planes of the crossed nicols by observing under the microscope (fitted with ocular and centered objective but not with condenser, and pointed directly at the sun) a cleavage plate of some mineral, as anhydrite, celestite, or anthophyllite, which shows parallel extinction. The cross-hairs of the ocular should then be parallel with the cleavage edge of the plate in its position of total extinction. (3) Insert the condenser and note that it is properly centered when the image of the substage diaphragm occupies the center of the eye-circle of the ocular. In this plan of adjustment the assumption is properly made that the draw-tube and the substage are in alignment and that the optical elements are correctly mounted—mechanical details which are satisfactorily met by modern instrument-makers.

THE OPTICAL PROPERTIES OF MINERALS

Passing now to the optical and crystallographical features on which mineral diagnosis under the microscope is based, we shall consider first their nomenclature. Both theory and experience have shown that for monochromatic light the variation in the optical properties of a given mineral with the direction can be adequately expressed and defined in the most general case by

reference to a triaxial ellipsoid, the principal axes of which are equal to the three principal refractive indices. Having given the lengths and positions of the three principal axes of this *optic ellipsoid* within the crystal, it is possible to predict definitely the optical behavior of any section cut from the crystal. The validity of the optic ellipsoid has been proved so frequently and its usefulness in practical work is so great that its importance, independent of all theory, in optical work cannot be too strongly emphasized. That this has not been adequately done in the past, is evident from the current terms used to designate the optical properties of a mineral and of a mineral section. Thus we determine whether a mineral is isotropic, uniaxial, or biaxial and classify it accordingly, but there is no collective term which states that by this determination we actually ascertain the particular type of optic ellipsoid by which the optical behavior can be expressed; whether by a triaxial ellipsoid in which the three principal axes are unequal, or by an ellipsoid of revolution in which one axis is unique and different in length from the other two equal axes, or by a sphere in which all three axes are of the same length. For this characteristic the term *optic ellipsoidity*[1] is here suggested as a suitable group expression; thus the *optic ellipsoidity* of a *biaxial* mineral may be considered *biaxial* (two axial ratios being required to define the shape of its ellipsoid); the *optic ellipsoidity* of a *uniaxial* mineral, *uniaxial* (one axial ratio being sufficient to define the shape of its optic ellipsoid); and the *optic ellipsoidity* of an *isotropic* mineral, *isoaxial* (the three axes of its optic ellipsoid being equal). The *optic ellipsoidity* of a mineral is one of its most important diagnostic features; it is employed as a primary group-characteristic in nearly all the determinative tables for use with the petrographic microscope which have been published.

The lengths of the principal axes of the optic ellipsoid are ascertained by measuring the *principal refractive indices* of the crystal. From these in turn the *principal birefringences*, the *optic axial angle*, and the *optical character of the mineral* can be derived; these last properties are, therefore, subordinate, in a

[1] The writer is indebted to Mr. C. E. van Orstrand of the U.S. Geological Survey for aid in devising both this term and the expression *optic ellipsily* noted below.

measure, to the refractive indices. But in ordinary mounted, thin sections no satisfactory method has yet been devised for measuring the refractive indices directly and the microscopist is forced, in consequence, to make use of the other properties which can be ascertained under these conditions but which do not express, even in aggregate, all the information embodied in the simple statement of the refractive indices. It is for this reason especially that so much emphasis is placed on methods for refractive index determination and in particular on the immersion method by means of which the refractive indices of minute, isolated mineral grains 0.01 mm. and over in diameter can be readily measured with a fair degree of accuracy.

For the complete description of the optical behavior of a mineral, it is essential to determine not only the lengths of the principal axes of the optic ellipsoid but also its position within the crystal. This is usually accomplished by means of *extinction angles* on crystal faces of known orientation. From the position of the optic ellipsoid within the crystal we are able to infer the system in which the mineral crystallizes, since this position depends, as Brewster was the first to show, on the symmetry of the crystal itself. By determining the *principal refractive indices* of a mineral and its *extinction angles* on plates of known orientation, we can thus define its *optic ellipsoid* and its *crystal system* and from these in turn derive the optical behavior of any section cut from the crystal.

Having given the optic ellipsoid of a mineral for a particular color of light, the directions of vibration (positions of extinction between crossed nicols) and the relative velocities of light waves entering normally to any given section of the mineral can be ascertained by considering the section to pass through the center of the optic ellipsoid and to cut out of the same an ellipse, along the major and minor axes of which the light vibrations take place and produce plane-polarized light waves, whose velocities of transmission are inversely proportional to the lengths of these axes. This ellipse may be called the *optic ellipse* of the section. The optic ellipse is completely defined when the length of its major and minor axes (refractive indices γ' and α') and their positions with

respect to some definite crystal direction in the plate (extinction angle) are given. In actual determinative work with thin sections, the lack of a satisfactory method for measuring refractive indices directly under the microscope is a serious difficulty and the observer is compelled to make use of other properties, as *birefringence* and the *relative axial lengths* or *axiality* of the *optic ellipse*, which can be determined under these conditions but which, as noted above, are less important than the refractive indices and do not express, even together, as much as the refractive indices do alone.

For the expression *axiality of the optic ellipse* the collective term *optic ellipsity* may be used to express the relative lengths of the axes of the optic ellipse of the section. This term is preferable to the usual term *optical character of the section or optical character of its elongation*. The term *optical character* serves primarily as a group expression for the terms *optically positive* and *optically negative*. Its further use, in the above sense as a term implying the determination, in plane-polarized light, of the relative lengths of the axes of the optic ellipse of any given section is not justifiable, because, in that case, the same term serves two masters and conveys to the mind two totally different impressions; and such usage is not conducive to precise statement. The term *optic ellipsity* or *axiality of the optic ellipse* may well be substituted for *optical character* in its second usage.

In practical mineral determination under the microscope the observer may ascertain, in monochromatic light: (*a*) the *optic ellipsoidity* of a mineral, whether *biaxial*, *uniaxial*, or *isoaxial;* (*b*) the absolute lengths of the principal axes of its optic ellipsoid ($=\alpha$, β, γ, the *principal refractive indices*); (*c*) the difference in absolute lengths of any two of the principal axes of its optic ellipsoid (=*principal birefringences*); (*d*) the angle between the normals to the two circular sections of the optic ellipsoid (=*optic axial angle*); (*e*) the principal axis which bisects the acute angle between the normals to the two circular sections of the optic ellipsoid (the *acute bisectrix* γ or a and with it the *optical character of the mineral* whether *positive* or *negative*); (*f*) the relative position of the optic ellipsoid within the crystal (usually ascertained by

means of *extinction angles* on known crystal faces) and with it the *crystal system* of the mineral.

Similarly for any given crystal section we can determine, in parallel polarized light, (*a*) its *optic ellipsity* or the *axiality of its optic ellipse* (relative lengths of the two axes of its optic ellipse); (*b*) its *refractive indices* γ' and a' (lengths of the major and minor axes of its optic ellipse); (*c*) its *birefringence* (measured by the difference in lengths of the major and minor axes of its optic ellipse); (*d*) relative positions of the axes of its optic ellipse to any crystallographic direction observed on the section (*extinction angle*).

These properties vary to a certain extent with the color of light used and give rise to phenomena of color and color dispersion which are useful in mineral diagnosis. These are briefly: *color; pleochroism; absorption; dispersion of mineral; variation in the principal birefringences; dispersion of the bisectrices; dispersion of the optic axes.*

With this brief statement in mind of the optical features which are made use of in practical mineral determination, it will now be in order for us to show that the methods of microscopical petrography measure up to the requirements emphasized in the introduction and are furthermore simple and easy of application. For this purpose it will be convenient to group the optical and crystallographic properties into two classes: those of the first class (*optic ellipsoidity, optic ellipsity, optical character of mineral, color, pleochroism, absorption, dispersion of the optic axes, dispersion of the bisectrices, crystal habit*) being ascertained ordinarily by direct observation without measurement, while for the second class (*refractive indices, birefringence, extinction angles, optic axial angles, cleavage angles*) the numerical results of actual measurement are required. This distinction is drawn somewhat arbitrarily and is not meant to imply that the properties of the first group are strictly qualitative in their nature but that they are treated at the present time in ordinary petrographic microscopic work as qualities of an object rather than quantities which must be definitely measured. With greater refinement in the methods of determination, some of the properties of the first class will un-

doubtedly be included in the second essentially quantitative group. In the following paragraphs a concise description of the essentials of a few of the best available methods for the determination of these properties will be given.

DETERMINATION OF THE OPTICAL PROPERTIES OF THE FIRST CLASS

For this group few new methods of determination have been developed in recent years; *color*, *pleochroism*, *absorption*, *crystal habit*, *dispersion of the optic axes and of the bisectrices* being ascertained by practically the same methods which have been in use since the introduction of the petrographic microscope.

The optic ellipsoidity.—In the determination of this feature, two methods, in particular, have proved useful in recent years: (*a*) Uniaxial minerals are readily distinguished from biaxial minerals, by noting that the achromatic brushes (zero isogyres) in interference figures from uniaxial plates are parallel with the principal nicol planes and pass through the center of the field on rotating the stage, while in biaxial minerals the dark bars (zero isogyres) of the interference figure rotate on rotation of the stage and may include any angle with the principal plane of the polarizer. If the dark axial bar in an interference figure does not remain straight and in the same azimuth on rotating the stage, the optic ellipsoidity is biaxial; otherwise the birefracting mineral is in general uniaxial.[1] (*b*) To ascertain whether a very weakly birefracting plate is isotropic or birefracting and at the same time to determine the relative value of the axes of its optic ellipse (its optic ellipsity), the sensitive tint plate should be inserted, not in the diagonal position as is usually the case, but in such a position that the axes of its optic ellipse include only a small angle with one of the principal nicol planes; under these conditions the field illumination due to the sensitive tint plate itself is very slight while its path difference is still effective. The changes in the faint color hues from the mineral grain are clearly visible against the darker background and extremely minute traces of birefringence can thus

[1] See F. Becke, *Denkschr. Wiener Akad. Wissen. Math.-Natur. Kl.*, LXXV, 1904; *Tscherm. Min. Pet. Mitteil.*, XXIV, 30, 1905; XXVII, 177–78, 1908.

be detected.[1] If the sensitive-tint plate be inserted in the diagonal position, it illuminates the field so strongly that the faint color differences from the mineral grain are veiled and often completely lost to view, especially if the grain be minute. The same method is applied with equal success to the determination of the optical character of very weakly birefracting minerals in convergent-polarized light.

The optical character can be determined on all sections in which at least one optic axis appears in the field by noting that the convexity of the axial bar (zero isogyre) passing through the optic axis is always directed toward the acute bisectrix.[2] On sections, perpendicular to the optic normal the acute bisectrix can be located by noting that the faint achromatic hyperbolas of the interference figure pass out of the field in the direction of the acute bisectrix[3] on rotating the stage. In case the plate is so thick that the interference colors are bright, the position of the acute bisectrix can also be ascertained by noting that the interference color is relatively lower in the quadrants containing the acute bisectrix than in the adjacent quadrants.[4] In thin rock sections the mineral plates of weak to medium birefringence do not often exhibit interference colors much above pale yellow of the first order and for such plates the second method is inadequate and the first should be used. The relative value of the acute bisectrix whether

[1] See F. E. Wright, "The Methods of Petro. Microsc. Research," Carnegie Inst. Washington, *Pub. 158*, 73, 1911. In the writer's microscope the sensitive tint plate is mounted in a rotating collar beneath the substage condenser and can be turned quickly from one quadrant to another, thus greatly facilitating its use in rapid routine work.

[2] The following concise statement of the rule for finding the sign of reaction of a section has recently been given by F. Rinne (*T.M.P.M.*, XXX, 321–23, 1911): A central uniaxial interference figure divides the field into four quadrants. Let the NE and SW quadrants be considered positive as usual and the adjacent quadrants negative. In biaxial minerals the areas NE and SW of the achromatic brushes (zero isogyres) taken with respect to the acute bisectrix may in like manner be considered positive. If now the sensitive tint plate be inserted so that the major axis γ of its optic ellipse points NE, SW, then the mineral is *optically positive* when the *positive quadrants or areas* of the interference figure are colored *blue* and *negative* when the *negative areas* are colored *blue*.

[3] F. E. Wright, *Amer. Jour. Sci.* (4), XVII, 387, 1904.

[4] F. Becke, *T.M.P.M.*, XVI, 181, 1897.

α or γ (the *optic ellipsity* of the section) can then be ascertained by use of the sensitive tint plate or by the quartz wedge in parallel polarized light.

MEASUREMENT OF THE OPTICAL PROPERTIES OF THE SECOND CLASS

A number of new methods have been suggested in recent years for the measurement of the optical properties of this class, with the result that satisfactory methods are now available for use even on minute mineral grains; the accuracy of the results attainable by these methods under the different conditions is known and the application of these methods is now a matter of routine.

Refractive indices.—For the measurement of refractive indices of minerals in the mounted thin section no accurate method has yet been devised; but on unmounted mineral grains and plates, measuring 0.01 mm. and over in diameter, the refractive indices can be readily determined by the immersion method with an accuracy of ±0.001 for sodium light on isolated favorable sections. For this method a set of liquids of known refractivity is essential. The following set is used at present in the Geophysical Laboratory:

Refractive Indices	Mixtures of
1.450–1.475	Kerosene and turpentine
1.480–1.535	Turpentine and ethylene bromide or clove oil
1.540–1.635	Clove oil and α-monobromnaphthalene
1.640–1.655	α-monobromnaphthalene and α-monochlornaphthalene
1.660–1.740	α-monobromnaphthalene and methylene iodide
1.740–1.785	Sulfur dissolved in methylene iodide
1.790–2.050	Methylene iodide, arsenic sulfide, sulfur and tin iodide.[1]
2.055–2.750	Glass produced by melting amorphous sulfur and selenium in different proportions. The mineral grains to be tested are immersed in the molten liquid but are examined after it has cooled and hardened to a red-colored glass.[2]

[1] Dr. H. E. Merwin of this laboratory has recently made a detailed study of these highly refracting mixtures, their preparation, and their permanency. The results of his work are to appear shortly in the *Amer. Jour. Sci.*

See also O. Maschke, *Pogg. Ann.* CXLV, 565, 1872; *Wiedemann's Ann.*, XI, 722, 1880; J. Thoulet, *Bull. Soc. Min. France*, III, 62, 1880; H. Ambronn, *Ber. Sächs. Gesell. d. Wissen. Math. Phys. Kl.*, 1–8, 1896; J. L. C. Schroeder van der Kolk, *Zeitschr. f. Wissen. Mikrosk.* VIII., 458, 1898; F. E. Wright, *T.M.P.M.*, XX, 239, 1901; *Amer. Jour. Sci.* (4), XVII, 385, 1904; Carnegie Inst. Wash. *Pub. 158*, p. 98, 1911.

[2] The refractive indices of these glasses were measured in lithium-light and not in sodium-light, as is the case with all the liquid mixtures in this list.

In this series the refractive index of each liquid for sodium light is 0.005 higher than that of the liquid immediately preceding it. In choosing these liquids the guiding factors were stability, miscibility, and low dispersion. The refractive indices were measured on a total refractometer up to 1.74; above this by the hollow-prism method in sodium light. In place of the hollow prism Dr. Merwin has recently found a prism satisfactory which is made by fusing two narrow strips of plane glass (selected microscope object glass) together at one end so that their plane surfaces below the joint include an angle of 35° to 45°. A drop of the highly refractive liquid is then placed in the wedge-shaped space between the glass plates and adheres by capillarity to their plane surfaces, thus assuming the required prism shape. The liquids are kept conveniently in small dropping bottles with ground-glass stopper and cap, which interposes two ground joints to prevent evaporation. Experience has shown that the liquids so kept do not vary over 0.002 in a year, while the average change in the refractive index of a liquid is about 0.001 decrease for every 3° C. rise in temperature. By using obliquely incident light or by observing the Becke line, it is possible to ascertain at a glance whether the refractive index of a particular grain is above, below, or about equal to, that of the liquid.

In case the mineral grain has a higher refractive index than the liquid, it acts as a lens on an incident pencil of rays and increases their convergency; if its refractivity is lower than that of the liquid, it diverges the incident rays. This difference in behavior is best shown by a pencil of oblique rays; these are concentrated on the distant side of a higher refracting mineral grain opposite to that at which the incident rays impinge; in a lower refracting grain they are concentrated on the near side. In both instances the two margins of the mineral grains appear unequally illuminated; if the light be incident from the left, the bright band of light appears on the right margin of the higher refracting grain, and on the left margin of the lower refracting grain. In case both mineral and liquid have the same refractivity for yellow or green light, the difference in dispersion between liquid and mineral gives rise to characteristic phenomena. The dispersion for liquids is in general

greater than that for solids and in the present instance the liquid will have a lower refractive index than the mineral for red and a higher refractive index for blue, with the result that the red rays are concentrated along the one margin of the grain and the blue rays on the opposite side. The grain appears fringed with colored margins, red or orange on the one side and pale blue on the opposite side. If the intensity of illumination on both sides of the grains is about equal, the refractive index of mineral and liquid are equal for the central part of the visible spectrum.

Obliquely incident light is most readily obtained by placing the forefinger between the substage reflector and the polarizer and casting a shadow over half the field. The error of such a determination in white light is less than ± 0.005 on good sections, while if monochromatic light be used and care taken to select clear single grains, the error may be reduced to ± 0.001. If the grain be anisotropic, the three principal refractive indices α, β, γ can be determined by placing the grain in such positions that the parallel polarized light waves from the lower nicol vibrate, in passing through the crystal, parallel to one of the three principal axes of the optic ellipsoid.

The chief difficulty in the measurement of the refractive indices of minute grains or plates in the thin section, is one of mechanical subdivision; the grains occur frequently in fine, overlapping aggregates, often imbedded in glass; and it is not an easy task under these conditions to find a clear, isolated grain on which measurements can be made.

The materials for the set of refractive liquids noted above can be readily obtained from dealers in chemical supplies and the entire series prepared for use in a few hours' time. With the set of refractive liquids at hand the refractive indices of a mineral grain can be readily ascertained within ± 0.005 and one of the most important optical constants of the mineral thus determined. It is a matter of surprise, in view of the ease and facility with which this method can be applied, that it is so little used by petrologists and by chemists.

Birefringence.—For the measurement of birefringence, extinction angles, and optic axial angles a specially constructed ocular

has been found convenient.[1] This ocular consists essentially of a metal holder, which fits into the microscope tube as an ordinary ocular and acts as a support for certain plates which are inserted in the lower focal plane of a Ramsden eyepiece above. Cross-hairs are attached to the base of the cylinder support for the Ramsden eyepiece and are viewed by it simultaneously with the upper surfaces of the inserted wedges or plates.

For the measurement of the birefringence a graduated combination quartz wedge is used which is so cut that the 0.1 mm. divisions of the scale on its upper surface give directly path differences in 10 $\mu\mu$ for sodium light. By its use together with a cap nicol, the path difference in sodium light or order of interference color in white light can be readily ascertained, the wedge being inserted in the diagonal position until the black band of exact compensation is reached; the division of the scale covered by the black band is then the path difference in 10 $\mu\mu$. In the case of thick plates the point of the line of compensation should be first determined approximately in white light; otherwise the correct line of compensation may not be selected when monochromatic light is used. The path difference is directly dependent on two factors: the thickness of the plate and its birefringence. The simplest method for obtaining the thickness of a mounted plate or grain is to focus with a high-power objective first on its upper surface and then on its lower surface, as seen through the plate or grain itself. The amount of movement of the fine adjustment screw during this operation is the apparent thickness of the plate or grain, provided, of course, the fine adjustment screw is accurately constructed. The true thickness is obtained by multiplying the apparent thickness by the average refractive index of the plate. Experience has shown that under these conditions an error of 5 or even 10 per cent[2] may be made, especially if the plate be very thin, on thicker plates and grains the percentage error, due to imperfect focusing, is correspondingly less. To insure greater accuracy, the average of a series of determinations on the same plate should therefore be taken.

[1] F. E. Wright, *Amer. Jour. Sci.* (4) XXIX, 415–26, 1910.

[2] See F. E. Wright, *Amer. Jour. Sci.* (4), XXIX, 416, 1910.

The quotient of the two values thus obtained—path difference divided by thickness of plate—is the birefringence. The probable error of the determination under these conditions with good sections may be 10 per cent; for ordinary minerals this means an error of one or more units in the third decimal place.

The extinction angle for a given crystal face is the angle between a definite crystallographic direction on the face and one of the axes of its optic ellipse. With sharply developed crystallites or with minerals exhibiting sharp cleavage lines the error resulting from incorrect setting of the crystallographic direction parallel with the vertical cross-hair in the ocular is practically negligible; with less sharply defined crystallographic directions, the settings are of course less accurate; but as this is due to the crystal development and not to the method, the observer can only accept the situation as he finds it; the only probable error over which he has direct control centers essentially in the determination of the position of extinction. Since the eye is sensitive only down to a certain limit (threshold value, on an average about 0.001 meter-candle), it is evident that for all positions of the crystal plate between crossed nicols for which the intensity of the emergent light is below this limit, the plate will appear dark. In ordinary microscope work the angular range of this area of darkness varies from 1° to 2°, depending on the conditions of illumination and the eye of the observer; the error of a single determination may amount to 1° under certain conditions. By repeating such determinations the probable error can be materially reduced. But more accurate results can be obtained by using special devices which have been constructed for the purpose. Of these the bi-quartz wedge plate[1] has the advantage of adjustable sensibility to meet the different conditions of observation which arise. It is a combination of a right-handed quartz plate with a left-handed quartz wedge, and of a left-handed quartz plate with a right-handed wedge, all cut normal to the axis and so mounted that the points of exact compensation in each half are in alignment. The position of extinction of a mineral is determined with this device by noting that, on its insertion, the parts of the mineral plate covered by the adjacent

[1] F. E. Wright, *Amer. Jour. Sci.* (4), XXVI, 377–78, 1908.

halves of the wedge show the same degree of illumination. If the mineral be not in the position of total extinction the halves are not equally illuminated. Experience has shown that with this device the probable error of a single setting on a favorable section is about $\pm 10'$. The bi-quartz wedge plate is mounted in a metal carriage which in turn fits into the ocular holder described above. This bi-quartz wedge plate may also serve on dark days for the adjustment of the nicols in the petrographic microscope.

Optical axial angles are most readily measured by means of the 0.1 mm. co-ordinate micrometer disk[1] which in its metal-mounting fits in the ocular holder noted above. On favorable sections (0.025 mm. and over in diameter) the probable error of measurements with this plate is about $\pm 1°$ in case both optic axes appear in the field of vision and $\pm 3°$ in case only one optic axis is visible. For measurements on mineral grains, the particles should be immersed in a liquid of the refractive index β to eliminate errors due to refraction on the uneven surfaces of the grains. In weakly birefracting substances and interrupted sections the axial bars are less sharply defined and the values obtained thereon are correspondingly less accurate.

The divisions of the co-ordinate micrometer disk serve to locate the position of any point in the field. The interference figure, observed, is practically an orthographic projection of the interference figure formed in the upper focal plane of the objective and the use of co-ordinates to locate points in the field is therefore permissible. The angular values represented by these co-ordinates are determined, once for all, by means of an Abbe apertometer, or a graduated sphere or a scale in the lower focal plane of the substage condenser.[2] In case both optic axes, A_1 and A_2, appear in the field the course of procedure is simple. The crystal plate is turned until the plane of the optic axes, A_1A_2, in the interference figure (observed, together with the co-ordinate micrometer scale after insertion of the Bertrand lens, in the lower focal plane of the

[1] F. E. Wright, Amer. Jour. Sci. (4), XXIV, 316–69; XXIX, 423, 1910; XXXI, 157–211, 1911.

[2] These are discussed at length in *Amer. Jour. Sci.* (4), XXIV, 317–69, 1907; also in Carnegie Inst. Washington, *Pub. 158*, 1911.

Ramsden ocular) is parallel with the horizontal cross-hair of the ocular and its distance in this position from the center of the field recorded. The crossed nicols are then turned through a suitable angle (30° or 45°). The axial bars rotate in the opposite direction but the optic axial points, A_1 and A_2, remain stationary and dark; they are situated at the intersection of the axial bars with the horizontal line which marked the plane of the optic axes. The angular distance between the two optic axial points A_1 A_2, thus determined, is directly the optic axial angle $2E$ in air.

In case only one optic axis A_1 appears in the field of vision the method is more complicated and less accurate but in view of its usefulness it may be briefly outlined. It is based primarily on the rule of Biot-Fresnel which states that for light waves propagated in any given direction in a crystal the two lines of vibration bisect the angles between the projections of the two optic axes on the plane normal to the given direction of propagation. In an interference figure the line of vibration for any point which appears dark between crossed nicols is evidently contained in the extinguishing plane of the analyzer—otherwise it would not be dark. The plane of vibration for all points on the achromatic brushes (zero-isogyres) of an interference figure is therefore known. By locating the optic axis A_1 and any point P on the achromatic brush it is accordingly possible by applying the Biot-Fresnel rule to determine graphically the position of the second optic axis.[1] After having made the measurements in the interference figure, the observed co-ordinate values are first reduced to equivalent angular values in air and these in turn to corresponding values within the crystal by means of its average refractive index. These angles are then plotted in suitable projection (angle or stereographic)—the plane of the optic axes as a great circle parallel with the horizontal diameter, the principal plane of the polarizer in its two azimuths as diameters of the projection, the optic axis A_1 and the point P on the achromatic brush at the intersection of the recorded small circle (almucantar) co-ordinates. In this pro-

[1] See F. Becke, *T.M.P.M.*, XXIV, 35–44, 1905; XXVIII, 290, 1909; also F. E. Wright, *Amer. Jour. Sci.* (4), XXIV, 316–69, 1907; (4), XXXI, 157–210, 1911; Carnegie Inst. Wash. *Pub. 158*, 147–200, 1911.

jection the Biot-Fresnel rule is applied by first projecting the optic axis A_1 on the polar circle of the point P; the intersection, C, of this polar circle with the diameter which defines the position of the principal plane of the polarizer at the time of the observation determines in projection the line of vibration of P. The angle between the point C and the projection point A'_1 of the optic axis A_1 is half the angle between the lines of projection of the two optic axes. The point A'_2, the projection of the second optic axis A_2, is accordingly found by laying off on the polar circle from the point C an angle equal to A'_1C. The intersection of the great circle through P and the point A'_2 with the plane of the optic axes is obviously the second optic axis A_2 and the angle between the two axial points, A_1 and A_2, is the optic axial angle $2V$. The best results are obtained by this method on sections in which the optic axis A_1 is located about midway between the center and margin of the field and the point P on the achromatic brush in a similar position. As noted above, a probable error of $\pm 3°$ is possible with this method even on the most favorable sections. The error is proportionately larger on poor sections.

GEOPHYSICAL LABORATORY
WASHINGTON, D.C.
March 16, 1912

GLACIATION IN THE TELLURIDE QUADRANGLE, COLORADO

ALLEN DAVID HOLE[1]
Earlham College, Richmond, Ind.

OUTLINE

PART I

Location and Extent of Area
Drainage
Topography
Geological Formations
Literature Concerning Glaciation in This and Adjacent Quadrangles
Glacial Phenomena of the Quadrangle
Description of Areas Glaciated in the More Recent Epoch

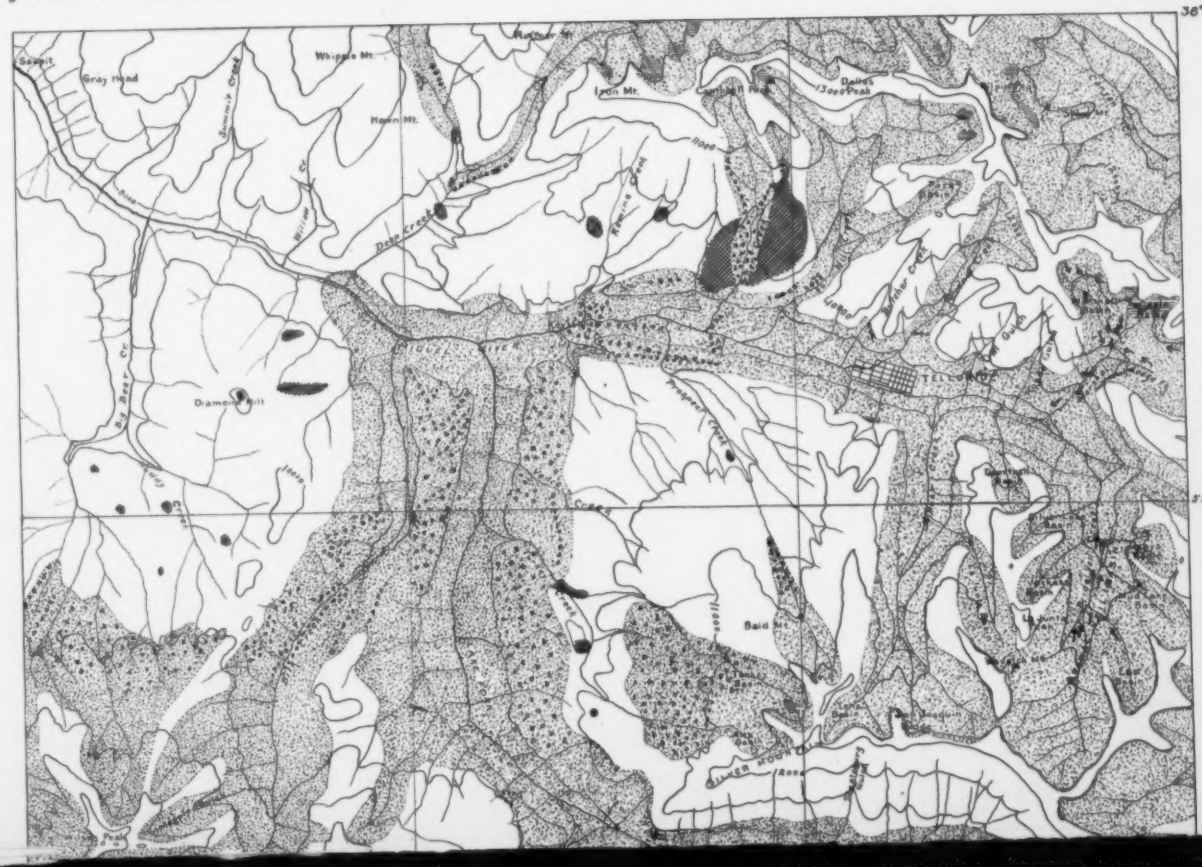
PART II

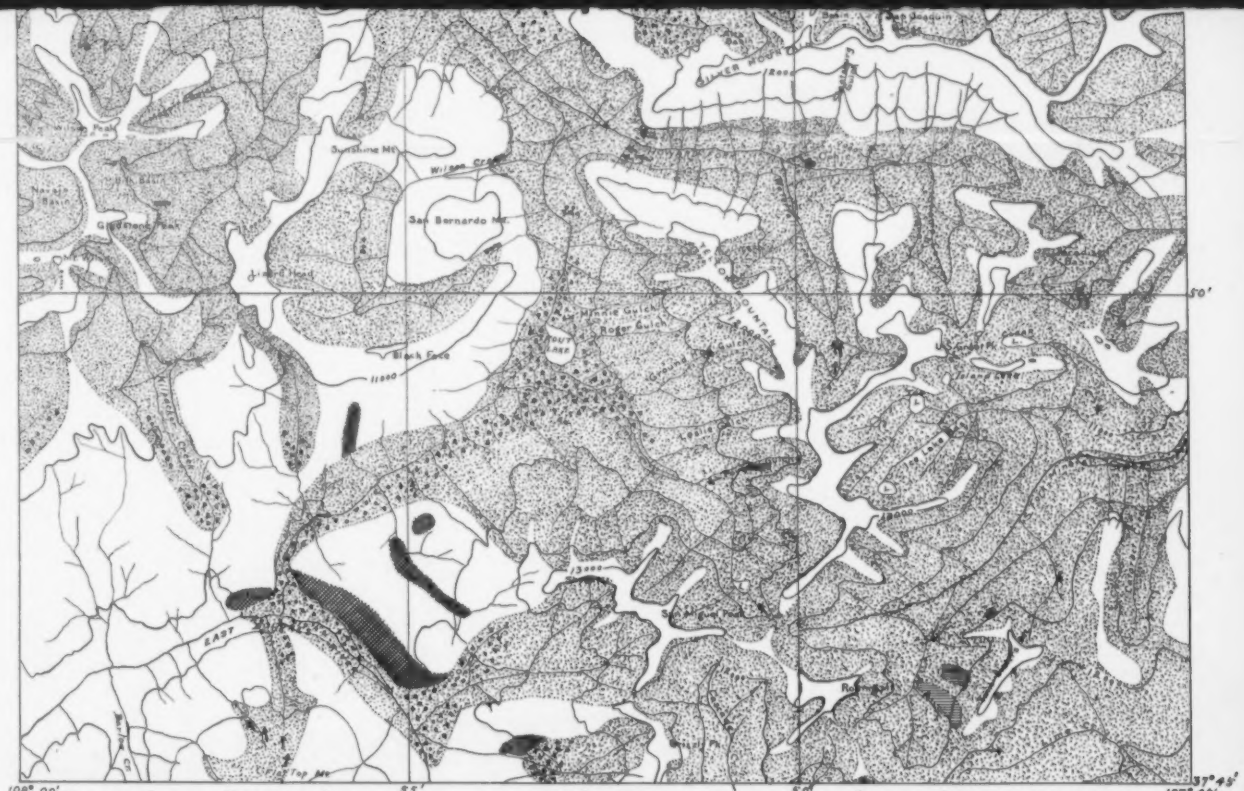
Description of Areas Glaciated in the More Recent Epoch (*continued*)

PART III

Description of Deposits of Earlier Drift
Landslides
Rock Streams
Summary and Conclusions
Topographic Effects of Glaciation
Cirques
Hanging Valleys
Rounded Topographic Forms
Silted-up Lakes and Ponds
Terraces and Valley Trains

[1] This paper presents primarily the results of work done by the author in the field seasons of 1904 and 1905, under the direction of Professor R. D. Salisbury. Acknowledgments are due, besides, to many observers who have done work in the same region, particularly to Mr. Whitman Cross, who has for some years been in charge of the general geological investigations in the San Juan Mountains, to Mr. L. L. Everly, who assumed equal responsibility with the author in the work of the first season, and to Mr. John T. Haworth, who rendered service as field assistant in the second season. —A. D. H.


36°00
Gravel
Gray road
Whipple Mt.
Iron Mt.
Kelso Mt.
Dalton Peak
13000
Big Bear Cr.
Diamond Hill
Bald Mt.
Lower Bear
Bear Valley
Baldwin
Big Bear City
Sugarloaf
Erwin Lake
Metcalf
Holcomb
Creek
Fawnskin
Stanfield Cut-off
Rattlesnake
Summit
Moonridge
Pine Knot
Big Bear Lake
Big Bear Dam
Big Bear Valley
Big Bear Lake
Big Bear Dam
Big Bear Valley
Big Bear Lake
Big Bear Dam
Big Bear Valley



MAP OF THE TELLURIDE QUADRANGLE, COLORADO

Showing the distribution of glacial formations. Glacial geology by Allen D. Hole, in 1904 and 1905, under the direction of Rollin D. Salisbury

V

2

8

Characteristics of the Deposits of Drift of the Earlier and the Later Epochs
Extent of Glaciation
In the More Recent Epoch
In the Earlier Epoch or Epochs
Age of the Drift
More Recent Epoch
Earlier Epoch or Epochs
Post-glacial Changes
Glaciation as Affecting the Location of Mining Claims

PART I

LOCATION AND EXTENT OF AREA

The Telluride quadrangle, Colorado, lies in the southwestern part of the state about 60 miles from the western and 55 miles from the southern boundary. It is included between meridians 107° 45′ and 108° 0′ west longitude, and parallels 37° 45′ and 38° 0′ north latitude, having therefore a width of a little less than 14 miles, a length of a little more than 17 miles, and an area of over 235 square miles.

DRAINAGE

The greater part of the area of the quadrangle is drained by the San Miguel River, which flows northwest to join the Dolores, a tributary of Grand River; but the Uncompahgre River to the north, the Animas to the southeast, and headwaters of the Dolores to the southwest each receive some streams heading within this area; so that streams flow outward across the borders of the quadrangle toward practically all points of the compass, finally, however, to join their waters with those of the other tributaries of the Colorado River before reaching the sea.

TOPOGRAPHY

The chief topographic features of the quadrangle may be grouped under three heads, viz.:

1. The rugged peaks and ridges in the eastern half of the area, a part of the San Juan Mountains.

2. The isolated, loftier peaks of the Wilson group in the central part of the western half.

3. The plateau north and south of the Wilson group, cut by deep canyons in which flow the San Miguel, and the East Dolores rivers and their tributaries.

The highest point in the quadrangle is Mt. Wilson, near the western side, 14,250 feet above the sea; numerous peaks, however, in the eastern half rise above 13,500 feet, and ridges extend for miles with crests at an elevation greater than 13,000. The lowest point in the quadrangle is in the canyon of the San Miguel River, in the northwestern part, an elevation of 7,500 feet; but the plateau in which the canyon is cut has at most points an elevation of not less than 9,000 feet.

The topographic features as they exist today in the quadrangle are the result of agencies which have been in operation from a remote period in the history of the earth to the present time. The earlier include all those forces and processes which culminated in the relative elevation of the land thousands of feet above the sea, the ejection of enormous quantities of lava and other volcanic material, and the dissection of this elevated and ejected material by erosion, until, at the opening of Pleistocene time, the mountains, plateaus, and main stream channels must have had positions relatively much the same as they have now. The details of the topography, however, are due to agencies which have operated within Pleistocene and recent times; chief among these agencies which have produced results more or less well marked are: (1) agents of weathering, including freezing and other changes in temperature; (2) running water; (3) lakes and ponds; (4) moving masses of snow and ice, not glacial; (5) landslides; (6) glaciers.

GEOLOGICAL FORMATIONS

Observations in regard to the geology and topography of areas within this quadrangle have been made by a number of scientists, including members of the Hayden Survey and representatives of the War Department of the United States, as well as many others; the first detailed work to cover the entire area, however, was that undertaken by Mr. Whitman Cross and his associates, the results of which were published by the United States Geological Survey in the *Telluride Folio*, in 1899, from which the summary given below is largely taken.

Speaking generally, it may be said that so far as rocks near the surface are concerned, the plateau portion of the quadrangle is for the most part underlain by sedimentary formations, while the peaks and ridges in the mountainous portion are composed very largely of igneous rocks. Of the latter there are (1) various phases of intrusive bodies which in form include stocks, laccoliths, dikes, and sills, and in composition range from basalt to rhyolite, including andesite,

FIG. 1.—Dike in sandstone on the north side of the San Miguel River, one-fourth of a mile northeast of the mouth of Big Bear Creek. Looking northeast from a point 100 feet above the stream.

gabbro-diorite, diorite-monzonite, diorite-porphyry, monzonite, and granite-porphyry; and (2) widespread sheets of bedded extrusive rocks of three series named in order from the oldest, the San Juan, the Silverton, and the Potosi rhyolitic series.

The intrusive bodies vary in size from dikes whose maximum thickness is to be expressed in feet and inches, and which at best have contributed only in the most insignificant degree to the physiographic and structural features of the region (Fig. 1) to

stocks whose dimensions are to be expressed in miles, and which have given rise to many of the loftiest and most rugged peaks to be found within the area, as for example the Wilson group (Fig. 2) and Grizzly Peak.

With the exception of a few small outlying remnants, the bedded volcanic rocks are found only in the eastern half of the quadrangle where they form the lofty and rugged peaks and ridges of the San

FIG. 2.—The Wilson group of mountains, an eroded stock. Looking south of west from elevation about 11,200 feet at the mouth of Alta basin. The body of water shown in the foreground is a small temporary glacial lake formed by unequal distribution of drift.

Juan mountain front. The lowest member, the San Juan series, consists of andesitic tuffs, breccias, and agglomerates, cemented to some extent by minerals such as calcite deposited by circulating waters, so that in favorable positions steep, clifflike slopes are formed. Its maximum thickness is 2,000 feet. The intermediate series, named, after the publication of the *Telluride Folio*, the Silverton series, consists of alternating andesitic and rhyolitic flows with which are mingled sheets of tuff and breccia of andesite and

rhyolite, making up a maximum of 1,300 feet in thickness. This series results in topographic forms similar in some situations to those resulting from the erosion of the San Juan series, in others more closely resembling the steeper cliffs of the Potosi rhyolite. Of the upper, Potosi rhyolitic series, a maximum thickness of about 1,300 feet remains, consisting of a series of rhyolitic beds, the majority of which are flows, but some are tuffs. The area covered by this series in the quadrangle is comparatively very small, but topographically it is conspicuous, not only because it forms the summits of the highest peaks and ridges, but also because it weathers in remarkably steep cliff faces, showing often a vertical columnar structure, and where the direction or degree of the slope changes, bold, sharply angular outlines.

Below the bedded volcanic rocks in position there occur in order the following sedimentary strata, viz.: (1) the Telluride conglomerate, (2) Cretaceous shales and sandstones, (3) Jurassic shales, sandstones, and limestones, (4) Triassic sandstone and conglomerate, and (5) some sandstone and conglomerate probably of Permian age.[1]

These sedimentary rocks have influenced in various ways the course of events in the geological history of the quadrangle, and have been important factors in producing certain conspicuous topographic forms found there at present, as for example the steep walls of the canyon of the San Miguel River, due in many places to the presence of sandstones and conglomerates. For the most part these sedimentary strata retain their horizontal position except in certain cases in the immediate vicinity of bodies of intrusive volcanic rocks; one conspicuous monocline, however, is to be found west of the mountain front, and folds somewhat more complex in the southeastern corner of the quadrangle.

LITERATURE CONCERNING GLACIATION IN THIS AND ADJACENT QUADRANGLES

1877. The Hayden Geological Survey.—In Appendix A to the *Ninth Annual Report of the United States Geological and Geographical Survey of the Territories*, Dr. F. M. Endlich reports, under the heading "Ancient Glaciers in Southern

[1] Cross, *Engineer Mountain Folio*, p. 7, and various other publications there referred to.

Colorado," pp. 216–26, evidences of glaciation at a number of points in the San Juan Mountains. These evidences include *roches moutonnées*, grooved and striated rock in place, shallow lakes, and glacial drift in the form both of scattered erratic bowlders and moraines. As to the time relations involved, Dr. Endlich concludes (1) that at least one glacier, called by him the Conejos, was not older than late Tertiary time, and might be much more recent, basing his conclusion on the relation of its action to the basaltic lava flows; and (2) that the glacier which descended the Animas valley was of older date than those whose effects were to be seen near the headwaters of the different streams named. He does not, however, seem to mean that there were two separate stages of glaciation. The total work done by glaciers in modifying the preglacial topography he considers to have been slight; aside from this no estimate is made as to the amount of glacial erosion, amount of ice, or area covered when the ice was at its maximum.

1883. R. C. Hills.—In the *Proceedings of the Colorado Scientific Society*, Vol. I, in an article entitled "Extinct Glaciers of the San Juan Mountains," pp. 39–46, Mr. Hills cites evidences of glaciation from numerous points, and makes certain estimates as to the extent of the ice and the time relations involved. The following summary shows the more important points presented:

1. The ice attained a greater thickness and covered an area many times more extensive on western than on eastern slopes.

2. Glaciers were not confined to existing valleys, but at some remote period probably the entire western slope of the mountains, except perhaps the higher peaks, was covered with an unbroken sheet of ice. As evidence supporting this conclusion he mentions (*a*) the presence of large granite bowlders distributed 5 miles west of Durango; (*b*) erratics of eruptive rocks on mesas flanking the San Miguel River 35 miles from the source of the river; and (*c*) erratic bowlders within a short distance of Montrose.

3. The Animas Glacier was 1,200 to 1,500 feet thick "between Elbert and Silverton," and nearly 3 miles wide "a short distance above Elbert."

4. During the period of extension of the ice sheet the erosion of Upper and Middle Cretaceous rocks amounted to 200 to 500 feet.

5. Box canyons 50 to 100 feet deep have been eroded since the retreat of the local glaciers as in the Uncompahgre valley at Ouray and in the Animas valley above Elbert, etc.

6. The total extent of the old ice envelope is estimated at more than 4,500 square miles.

1893. George H. Stone.—In Vol. I of the *Journal of Geology*, pp. 471–75, Mr. Stone describes glacial phenomena found in the valley of the Las Animas River, and in some of the valleys tributary to it above Silverton. The moraines near Durango are noted, but the difference in age between the drift on the edge of the mesa lying east of the city and that lying near Animas City but little above the level of the river seems not to have been recognized. The total length of the Animas Glacier is given as about 70 miles, average slope of upper

surface 83 feet or more per mile, thickness near Silverton, 1,500 feet. Attention is also called to certain facts, viz.: (1) that striations on rock in place are relatively rare on account of the character of much of the outcropping volcanic rock; (2) that a comparatively small amount of morainal material is to be found; and (3) that the amount of outwash gravels in the form of terraces and valley train is large.

1899. George H. Stone.—In *Monograph 34, U.S. Geological Survey*, pp. 340–45, Mr. Stone repeats substantially what was published in the *Journal of Geology* in 1893 in regard to glacial phenomena in the valley of the Las Animas, and adds notes on evidences of glaciation in other valleys of the San Juan Mountains, viz., the San Miguel, Uncompahgre, and upper Rio Grande; and mentions as glaciated the upper parts of the valleys of Los Pinos, San Juan, Navajo, Chama, and other rivers of the western slopes of the mountains. Moraines, erratic bowlders, *roches moutonnées*, and outwash gravels are mentioned, and locations are given for some of the best-marked instances of such phenomena.

1899. Whitman Cross.—In the *Telluride Folio*, p. 15, Mr. Cross records evidences of glaciation as follows: (1) in the upper parts of some valleys, *roches moutonnées*, striated and polished rock in place, small lake basins, and glacial cirques; (2) at lower elevations in the principal valleys and on some ridges, glacial deposits consisting of angular and subangular bowlders, gravel, sand, and finer material, sometimes in the form of small moraines, sometimes in isolated patches scattered over the surface. The largest area of drift mapped lies east of the Lake Fork of the San Miguel River and is referred to the action of a stream of water which, at a time when the ice moving down Lake Fork was higher than the canyon walls, was believed to flow during the summer in a channel along the eastern side of the glacier to join the main fork of the San Miguel River near Keystone. Aside from a suggestion that ice from Lake Fork seemed to be present at a later date than in the main fork above Keystone, the time relations are not discussed.

1900. Arthur Coe Spencer.—In the *Twenty-first Annual Report of the United States Geological Survey*, pp. 156–59, Mr. Spencer names as evidences of glacial action in the Rico Mountains (1) certain topographic features, (2) a few instances of polished and striated bed rock, and (3) some deposits of glacial débris. He concludes that the amount of ice present was small, and that the time covered by glacial conditions in this group of mountains was short.

1905. Whitman Cross.—In the *Rico Folio*, pp. 6, 12, and 13, the evidences of glaciation named by Mr. Cross are much the same as those named by Mr. Spencer in the work last cited; there is added, however, a suggestion of two distinct glacial stages, viz.: (1) a recent stage referable to the close of the Wisconsin period, and (2) a pre-Wisconsin stage. The morainal deposits, *roches moutonnées* and striae, are referred to the former; high-level bowlder beds are classified as pre-Wisconsin in age though not necessarily glacial in origin.

1905. Whitman Cross.—In the *Needle Mountains Folio*, pp. 6, 11, and 12,

evidences of glacial action are noted at numerous places. The amount of morainal drift remaining in the quadrangle is observed to be relatively very small; the extent of grooved and polished surface of bare rocks, very large. From evidences of the latter kind within the quadrangle and from other evidences in adjacent quadrangles, the conclusion is reached that when glaciation was at its maximum the "greater part of the Needle Mountains area was buried beneath a thick mantle of ice and snow, from which only the higher summits projected." Only one stage of glaciation is recognized so far as observations made in this quadrangle are concerned.

1905. Whitman Cross and Ernest Howe.—In the *Silverton Folio* numerous references are made to the evidences of glacial action at points in various parts of the quadrangle. As in the *Needle Mountains Folio*, the small amount of morainal material is noted, as well as the extensive development of cirques. The authors express the opinion that the amount of glacial erosion in the glacial epoch recognized in the Silverton quadrangle was slight.

1906. T. C. Chamberlin and R. D. Salisbury.—In Vol. III of their *Geology*, pp. 334–36, Chamberlin and Salisbury include the San Juan Mountains in the term "mountains of southwestern Colorado," and, in addition to noting the former size and the altitude of the source of the glaciers in these mountains, state that the drift is referable to two or more glacial epochs.

1906. Whitman Cross and Ernest Howe.—In a paper entitled "Glacial Phenomena of the San Juan Mountains, Colorado," published in the *Bulletin of the Geological Society of America*, XVII, 251–74, Cross and Howe cite the evidences of glaciation at various points in the San Juan Mountains as noted above, and make mention of conclusive proof of two distinct stages of glaciation obtained especially in the Uncompahgre valley in the Ouray quadrangle in the summer of 1904. The chief differences noted with respect to the drift deposits of the two stages are (1) the slight modification due to weathering and erosion in the more recent deposits; relatively great changes in both these respects in the earlier; (2) the occurrence of the older drift at a greater distance from the mountains, capping ridges, and hills which had been formed by erosion before the last stage of glaciation; and (3) stratified deposits of gravel associated closely with the older deposits at relatively high elevations, and a series of gravel terraces intermediate in position between these and the earliest valley trains of the more recent stage.

1907. Whitman Cross and Ernest Howe.—In the *Ouray Folio*, pp. 7 and 15, the authors present again substantially the same data and conclusions in regard to glaciation in the Ouray quadrangle as were included in their paper just referred to on glaciation in the San Juan Mountains.

1909. Ernest Howe.—In *Professional Paper 67, U.S. Geological Survey*, Mr. Howe refers briefly in a number of places to the evidences of glaciation in the San Juan Mountains, but records no observations not included in publications already named above.

1910. Stephen R. Capps, Jr.—In the *Journal of Geology*, XVIII, 370 and

371, Mr. Capps refers to the striking similarity between the "rock streams" found at various points in the San Juan Mountains, and the "rock glaciers" of the Nizina region in Alaska. In regard to the latter he reaches the conclusion that they "are now in motion, moving in some such way as a glacier."

1910. Whitman Cross and Allen D. Hole.—In the *Engineer Mountain Folio*, pp. 8 and 9, evidences are given leading to the conclusion that the mountains of the quadrangle were subjected to glaciation at two distinct periods separated by a long interval of time.

GLACIAL PHENOMENA OF THE QUADRANGLE

As may be seen by reference to the literature cited above on glaciation in the region, complete detailed observations on the glacial phenomena of the Telluride quadrangle have not heretofore been made. By far the most complete account of such phenomena yet published is contained in the *Telluride Folio*, already referred to; but even there little reference is made to the details beyond what is necessary in illustrating general statements; and, moreover, especial attention is called to the fact that no attempt has been made to represent on the map all the deposits of glacial débris that were recognized. The overshadowing importance at that time of a careful study of the intricate relations involved in the volcanic rocks, and the demand for an early publication of the results of such study for the benefit of the extensive mining interests of the region no doubt fully justified the omission of many of the details relating to glacial action; the striking character, however, of some of the phenomena observed, and the aid which an understanding of the relations involved promised to give in the determination of some unsettled points in Quaternary history led to a systematic examination of the glacial phenomena of the entire quadrangle, the report on which here presented constitutes, therefore, a supplement to the conclusions previously published.

The evidences of glacial action found in the Telluride quadrangle include most of the characteristic marks of the work of glaciers as found in other localities, viz.: (1) cirques, (2) striated bed rock, (3) *roches moutonnées*, (4) lakes in rock basins, (5) moraines both in the form of ridges and of broad sheets with irregular, hummocky topography including undrained depressions, (6) unassorted drift including fragmental material of all sizes from fine silt to bowlders,

18 feet in diameter, and containing representatives of the various kinds of rock present in the basins from which the drift was derived, (7) striated bowlders included in the unassorted drift, (8) streams steep in gradient flowing in valleys U-shaped in cross-section, and (9) hanging valleys. Of the evidences named above it was found that a part of that referable to classes 5, 6, and 7 represents the work of an epoch or epochs of glaciation earlier than the most recent. Some of this earlier drift occurs in or near valleys in which ice of the latest epoch was present; but some in valleys which appear not to have been subject to the action of ice of so recent a time. Furthermore, the earlier drift is in some cases found on divides between valleys instead of on the slopes or bottom as is usually the case with the more recent drift, and in many cases glaciated valleys contain drift of the most recent epoch only. In view of these facts in regard to the distribution of drift of different epochs, the detailed descriptions of glacial phenomena in different basins and valleys have been grouped as follows:

I. Phenomena in each valley referred to glacial action of the more recent epoch.

II. Phenomena referred to glacial action distinctly earlier in time.

DESCRIPTION OF AREAS GLACIATED IN THE MORE RECENT EPOCH

VALLEY OF THE SAN MIGUEL RIVER

The San Miguel River is formed by the junction of Ingram and Bridal Veil creeks about two and one-half miles east of the city of Telluride. The walls of the valley near this point are, for much of their height, bare precipices, and rise from 2,000 to 3,000 feet above the bed of the stream. The channel of Ingram Creek is a continuation in direct line of the valley of the San Miguel River; but from a point a half a mile above its junction with Bridal Veil Creek to the level of the lower part of Ingram Basin, a vertical distance of over 1,000 feet, the gradient of the stream is practically that of the slope of the walls of the valley of the San Miguel on either side, so that the steep side walls of the valley of the San Miguel virtually meet each other to the east, forming a cul-de-sac which differs from

a typical cirque only in the fact that its walls are deeply notched by permanent streams (Fig. 3).

Below this cirquelike valley head the height of the walls and the steepness of their slopes gradually diminish until, just above Keystone six miles to the westward where deposits in the form of moraines are abundant, the height of the walls is not more than

FIG. 3.—Valley of the San Miguel River, elevation 9,000 feet; looking south of east from north side of valley. Note the flat bottom, the meandering stream, and the abrupt termination of the valley in the center of the view.

400 to 600 feet with a slope not steeper, in general, than 30 to 40 degrees. This comparatively low elevation of the top of the valley walls above the stream as shown just east of Keystone is due in part to the fact that the San Miguel River at this point has its channel in glacial drift, or in the silt of a lacustrine deposit which fills the channel cut in the underlying bed rock to a depth of probably 400 feet. From the morainal deposits in the vicinity of Keystone to the terminus of the glaciated area near the mouth of

Deep Creek, the valley of the San Miguel is a canyon with precipitous walls 1,000 feet high. Beyond the mouth of Deep Creek the canyon gradually increases in depth until, at Sawpit, at the northwest corner of the quadrangle, the stream is 1,700 feet below the level of the edge of the plateau in which it has cut its channel.

Drift in the valley of the San Miguel.—Drift in the form of valley train is found up to 100 feet above the stream at various points as at Newmire and Sawpit, and beyond the boundaries of the quadrangle; but the lowest point reached by the ice in the more recent stage of glaciation is near the mouth of Deep Creek. At this point the north wall of the valley is precipitous, its south wall worn and weathered until, although still steep, it has become a long, retreating slope instead of a precipice. On the north side of the river here and for about one and one-fourth miles to the eastward, no glacial débris is discernible such as could be classed as morainal. The bare cliff faces afford no place for its lodgment; and even if once left on the more level area beside the stream, it has been either washed away or covered by irregular heaps of talus which have fallen since the ice withdrew.

On the south side, however, the longer, less steep canyon wall has allowed the glacial débris to remain in sufficient quantity to mark the approximate position of the edge of the ice at the time of its farthest advance. The débris consists of bowlders in variety, some with characteristic glacial striae, exposed at various points along the boundary as mapped and to the east of this line. In sharp contrast, the slope to the west of the boundary is covered by black soil, usually with few rock fragments, or, where they exist, consisting almost entirely of fragments of bed rock.

Between Bilk Creek and Lake Fork the south wall of the canyon becomes somewhat steeper; in the upper 200 or 300 feet, however, the slope affords lodgment for drift, forming a well-marked narrow shelf for a distance of more than a fourth of a mile. The top of the mesa to the south is entirely covered with drift to a depth which at its maximum may reach 200 or 300 feet. On the north side of the canyon, the wall is still precipitous, with no possibility for the lodgment of drift; but at a point opposite the railroad bridge over the San Miguel River, drift appears on the edge of the

mesa at an elevation of 9,000 feet, or about 1,000 feet above the stream. This drift consists of a narrow, thin sheet of glacial débris, with bowlders of granite and diorite-monzonite, some of them striated, mingled with a much larger number of sandstone bowlders and fragments which cannot be distinguished from the Dakota sandstone, which here forms the bed rock. Opposite the mouth of Lake Fork the drift is found farther north, covering an area which suggests a lobelike expansion of the border of the ice up the valley of the small tributary which enters from the north, and over the low divide northwestward into the upper part of the valley of a tributary of Deep Creek. At the point on the eastern side of the lobelike expansion, where the boundary of the drift returns to the edge of the canyon, a well-marked morainal ridge occurs. It has a length of about 20 rods, a height in some places of as much as 30 feet, and contains bowlders in variety up to five feet in diameter, some of them showing striations. Eastward from this morainal ridge the boundary of the drift leaves the top of the mesa, descending rapidly some 300 feet over the still steep canyon wall toward the conspicuous moraines which partially fill the valley of the San Miguel in the vicinity of Keystone.

The moraines below Keystone are formed from material brought partly by ice advancing down Lake Fork, partly by that coming down the main valley from the east. San Juan bowlders up to 15 feet or more in diameter characterize the drift from the east; granite or diorite-monzonite in bowlders up to about 3 feet in diameter, that from the south. The mesa lying in the angle between the main valley and Lake Fork is covered with drift brought from the south; this drift extends eastward more than half a mile from the nearly perpendicular rock face which at this point forms the upper part of the east wall of the canyon of Lake Fork. While there is more or less commingling of drift from the two sources, yet, speaking generally, the small tributary of the San Miguel River, which enters from the south about one mile east of Lake Fork is the dividing line between drift from the east and from the south. Half a mile west of this tributary and between the railroad and the San Miguel River, the moraines take the form of low ridges extending in a northeast-southwesterly direction. On the north side of the

river, and extending one-fourth to one-half a mile up the valley from this point, are glacial deposits which are being treated by hydraulic process to recover the gold they contain. These deposits, as well as those extending eastward for half a mile from the small tributary referred to, and lying chiefly on the south side of the river, show in places layers of stratified silt, sand, and gravel; the greater part of the deposit, however, is unstratified.

The drift in the vicinity of Keystone constitutes by far the largest accumulation of glacial débris to be found in the canyon of the San Miguel; judging from the comparatively small number of large San Juan bowlders found farther down the canyon, the Keystone drift is in the nature of a terminal moraine for the glacier which advanced from the east. On August 1, 1904, drift in the form of a ridge transverse to the stream at a point about four-fifths of a mile east of the mouth of Lake Fork was being washed down in the process of hydraulic mining; the work showed that the pre-glacial channel of the San Miguel River at this point was about 100 yards farther north than at present, and approximately parallel to its present course, and that the pre-glacial channel had a depth of bed as much as 30 feet lower than the bottom of the present channel. It appears, therefore, that the pre-glacial channel was filled to such an extent as to displace the stream and cause it to flow at a higher level along the south wall of the valley where it has in post-glacial time eroded a new channel not more than 10 to 20 feet in depth.

This accumulation of drift in the vicinity of Keystone is believed to have been chiefly responsible for the existence of a glacial lake which extended eastward from Keystone to a point beyond the city of Telluride, a distance of more than four miles; and as the greater part of this drift for a quarter of a mile or more below the mouth of Remine Creek contains numerous large San Juan bowlders, the drift chiefly responsible for the existence of the lake must have been brought by glaciers from the east. The date of this glacial lake is therefore fixed for the time just following the retreat of the ice up the San Miguel valley after depositing the drift at and below the mouth of Remine Creek. The silting-up of this lake has produced a flat-bottomed, comparatively level valley, as shown in Fig. 3. The surface of this valley is now about 400 feet higher than the

bottom of the pre-glacial channel of the San Miguel River exposed in the process of hydraulic mining below Keystone as referred to above.

In addition to the drift near Keystone, deposits distinctly morainal in character occur at two other points in the bottom of the valley. One of these points is between one-fourth and one-half a mile eastward from the mouth of Remine Creek; the other, just east of Eder Creek. Both of these accumulations are to be regarded as small recessional moraines. The westernmost one consists of almost bare, rounded hillocks about 60 feet higher than the level valley floor to the east, and with slopes of 25° or 30°; these hillocks constitute a narrow, but irregular belt across the valley somewhat convex downstream. The drift here consists of bowlders up to 6 feet in diameter, some of which are well striated, mingled with sand and clay. The varieties of rock present include Telluride conglomerate, quartzite and granite such as are contained in the Telluride conglomerate, sandstone both light-colored and red, and bowlders of the San Juan formation. Between this belt and the much higher, forest-covered morainal accumulation lying farther west than the mouth of Remine Creek, there is a depressed area occupied in part by ponds due to dams constructed by the Keystone Hydraulic Mining Company (Fig. 4). The second recessional moraine lying just east of Eder Creek consists of a much narrower, broken series of hillocks, likewise convex downstream. These hillocks are not more than 10 to 20 feet higher than the general level of the valley bottom. Like the first recessional moraine described, this one has bowlders in variety; but here, with the exception of San Juan bowlders up to 10 feet in diameter, they are small.

Lateral moraines along the San Miguel valley—south side.—From the low recessional moraine which lies east of the mouth of Remine Creek, a ridge of glacial drift extends eastward on the south side of the valley to Prospect Creek, a distance of half a mile. This ridge has an elevation of about 70 feet above the surface of the lacustrine plain forming the bottom of the valley, a height of crest above the depression to the south of not more than 20 feet at any point, and a width of from 10 to 150 feet. This ridge constitutes the only well-marked lateral moraine belonging to the late recessional stages of ice in the San Miguel valley.

Well-marked ridges or benches of glacial material corresponding in elevation to the upper parts of the drift accumulation near Keystone occur on the south side of the valley as follows:

1. Near Telluride, three-quarters of a mile west of Bear Creek. A small stream here enters the valley of the San Miguel from the south, and the moraine lies at an elevation of 9,750 feet across the mouth of the basin drained by this stream. The moraine is here a

FIG. 4.—Recessional moraine (in center), in the valley of the San Miguel River about a half-mile east of the mouth of Remine Creek. Water in depression to left is held by a dam. Elevation about 8,600 feet.

well-marked ridge, and stands 30 to 40 feet higher than the surface of the basin just back of it. In composition the ridge is made up of a variety of rocks: San Juan, Telluride conglomerate, light-colored sandstone, and an occasional piece of Dolores sandstone. Striated bowlders were found at the point where the stream has cut through the moraine. The total length of the well-marked ridge is something less than 80 rods. An effort was made a few years ago

to make a reservoir of the basin lying back of this ridge by filling up the stream-cut in the moraine; the dam thus formed has been largely washed away, but the name, the "Van Atta dam," is still used to refer to the part remaining. Below the moraine to the north, are two or three secondary ridges or benches, the one most plainly marked being about 250 feet below the principal ridge, that is, at an elevation of about 9,500 feet. From these ridges glacial drift covers the valley slope down to the river, nearly 1,000 feet below; bowlders up to 8 feet in diameter occur here.

2. A half-mile farther west another small tributary enters the San Miguel River from the south. The moraine here is not a well-marked ridge, but a level bench across the valley, showing sections of typical morainal débris.

3. From the point just named westward the moraine cannot be distinguished for about a mile and a half. The slope of the valley is steep, covered with a forest of spruce and aspen, and shows occasional outcrops of rock in place; little glacial débris could remain on this slope. But at a point about one-fourth of a mile east of the road which leads from the village of San Miguel up the south slope of the San Miguel valley, glacial drift appears in abundance at an elevation of about 9,550 feet on the crest of the ridge which divides the San Miguel valley from the valley of Prospect Creek, and continues as a well-marked ridge from this point westward to the deposits near Keystone. At the point where the road mentioned above crosses this ridge there is a notch some 50 feet or more in depth. Small, but distinct ridges of clay, gravel, and small bowlders lead off from the vicinity of this notch in a southwesterly direction toward the valley of a tributary of Prospect Creek. West of the notch referred to for half a mile or more the moraine consists of two distinct ridges or crests; the crests are never far apart, making thus a single ridge with a double crest rather than two separate ridges. The lower crest is always to the north, being from 50 to 100 feet lower than the other.

Through this double-crested lateral moraine Prospect Creek has cut a channel sufficiently deep to allow its basin to be drained, though it still lacks over 350 feet of having cut down to the level of the San Miguel River. The sides of the cut are steep where the

stream crosses the lower ridge of the moraine, exposing unassorted glacial drift with bowlders in variety, ranging in size for the San Juan bowlders up to nearly 20 feet in diameter; the depth of the cut is here about 50 feet. Where the stream crosses the higher ridge of the moraine the cut is comparatively broad, and about 150 feet deep. The area south of the moraine at this point shows some effects of ponded waters; the topography, however, is not such as is due to the silting-up of a lake; it is rather that of a flood-plain which has been somewhat eroded.

West of Prospect Creek gap the topography is not so simple as to the east. The lower ridge persists, but the higher one flattens out southward into a series of gentle swells, and finally joins a higher point west of the road which leads from Keystone up to the plateau to the southeast. This arrangement of the drift, together with the sharp turn that Prospect Creek makes to the northward just at the gap, indicates that the valley of Prospect Creek extended on to the northwest in pre-glacial time, joining the valley of the San Miguel River probably somewhere near Keystone.

Lateral moraines along the San Miguel valley—north side.—The most easterly point at which the lateral moraine is to be found on the north side of the valley is on the west side of Royal Gulch at an elevation of about 10,000 feet. The cut made by the road at this point has exposed a heterogeneous mixture of clay and bowlders, the latter chiefly from the San Juan and Telluride formations; some of the bowlders are striated. The amount of this deposit is comparatively small; that part deserving mention as decidedly morainic is included within a distance of less than 40 rods along the side of the valley.

Farther west, a short ridge of glacial drift occurs on the east side of Cornet Creek at an elevation of 9,800 feet, and on the east side of Butcher Creek at 9,650 feet, extending in each case from the eastern side of the valley to the stream channel, and rising 50 to 60 feet higher than the somewhat flattened area just to the north.

At the junction of the valley of Mill Creek with the San Miguel, no morainic ridge appears such as is found in the valleys of Cornet Creek and Butcher Creek. The ice from Mill Creek basin evidently had sufficient force to push out into the valley of the San

Miguel any débris which the glacier in the latter may have carried at its margin. On the west side of Mill Creek a morainic ridge extends in a direction south of west from an elevation of 9,500 feet down to about 9,100 feet; but this ridge is probably chiefly due to ice from Mill Creek rather than to that coming down the San Miguel valley.

No further remnants of a lateral moraine occur on the north side of the San Miguel valley until a point is reached about three-fourths of a mile east of Remine Creek at an elevation of 9,500 feet; beginning here, glacial débris forms the top of the ridge extending south of west to Remine Creek. At its eastern end this ridge is not so well marked as the moraine on the south side of the valley; farther west the ridge is more pronounced. One noticeable feature of this part of the moraine is the number of large bowlders which lie upon its southern slope. The elevation of the east end of this ridge, 9,500 feet, is about 300 feet higher than the crest of the lateral moraine on the opposite side of the San Miguel valley. This difference in elevation is probably the result of the change in direction of the course of the valley of the San Miguel. It will be noticed that at a point about halfway between Eder Creek and Remine Creek, the San Miguel River changes its course from north of west to south of west, a change of about 25°. The ice having motion in a north-of-west direction before reaching this point would not change its direction of movement readily, and so would crowd up on the north side just below the point in the valley where the change of course takes place.

Striae and striated bowlders in the San Miguel valley.—Striated bowlders occur in abundance in the drift in the San Miguel valley, both in the moraines near Keystone, and at practically all points farther east where there is any considerable accumulation of glacial débris.

Striae on rock in place were observed at three different locations, all on the north side of the valley; in each place a part of the striae are on a rock face of steep slope, and show dip in an upstream direction. This upstream dip is interpreted as being the result of the crowding-up of the glacier on the north side of the valley, due to the force of the ice entering from two southern tributaries, viz.,

Bear Creek and Bridal Veil Creek. The points observed and the measurements made are as follows:

1. At several points near the Old Smuggler Mill, near Marshall Creek. In one area, 60 feet above the mill at an elevation of 9,300 feet, the rock face forming the side of the valley has a slope of about 40°; the striae dip up the valley (eastward) 15° to 17°. In another area, 150 feet to the west, the dip up the valley is from 3° to 5°. The direction of the striae varies from N. 52° W. to S. 88° W.

2. One-fourth of a mile east of Owl Gulch at an elevation of 9,400 feet (500 feet above the bottom of the valley), sandstone forming the side of the valley has a slope of face of 60°; striae dip up the valley (eastward) 10°. Direction of striae about N. 87° W.

3. About one-fourth of a mile east of Owl Gulch at an elevation of 9,000 feet, a small reservoir has been constructed with a ledge of red sandstone for its bottom. At some places the sandstone exposes nearly vertical faces, and on such faces some of the striae have a dip up the valley of about 5°. Some of the striae on these faces have an equal or greater degree of dip down the valley; but there are a greater number of striae exposed which dip up the valley than down the valley. Striae here vary in direction from S. 63° W. to N. 78° W.

Thickness of glacial ice in the San Miguel valley.—In the cirque-like head of the San Miguel valley, two miles east of Telluride, the ice was probably not less than 1,500 feet in maximum thickness. In the neighborhood of Telluride, the maximum was about 1,000 feet, the thickness gradually decreasing westward to the neighborhood of Keystone.

VALLEY OF EDER CREEK

Ice of the more recent epoch filled the main valley of Eder Creek and extended to the edge of the glacier which moved down the valley of the San Miguel. The head of the valley is an excellent example of a glacial cirque. At the sides and head are long talus slopes with precipitous rock walls in places above them; on the bottom the talus fragments have been pushed into the successive ridges characteristic of rock streams.

A precipitous rock face at an elevation between 10,500 and

11,000 feet separates the cirque from the forest-covered portion of the valley below. Below the precipice, well-developed lateral moraines extend on either side of the valley down to about 10,000 feet in elevation. Below this point to the edge of the valley of the San Miguel, a distance of nearly a mile, the morainal deposits consist of an irregular grouping of hillocks, with a few fragments of ridges transverse to the valley. From the abundance of the moraines in the lower part of the valley, and from their arrangement partly as ground moraine and partly as recessional moraines, it seems probable that but little ice from the valley of Eder Creek was added to the glacier in the San Miguel valley.

In the valley of the east fork of Eder Creek, a glacier less than a mile in length existed in the later stage of glaciation. Above 11,000 feet in elevation the valley shows the rounded forms due to the effect of passing ice wherever rock in place outcrops in projecting ledges or points; back of the more level, rounded slopes are the precipitous faces of the bounding walls, with steep talus slopes, overgrown, in this valley, for the most part with scanty vegetation. Between 10,500 and 11,000 feet in elevation, the stream draining this tributary valley has a very steep-walled, V-shaped channel. In the bottom of the channel, and at some places for 10 feet to 20 feet up the sides, the Telluride formation outcrops; lying on the Telluride formation is glacial débris 30 to 40 feet thick, containing bowlders up to 4 feet in diameter, some of which are well striated.

The thickness of the ice in the valley of Eder Creek does not seem to have exceeded a maximum of 200 to 300 feet.

VALLEY OF MILL CREEK

The main valley of Mill Creek, heading south of Gilpin Peak, is broadly U-shaped above about 10,500 feet in elevation, becoming broader toward the upper end. Knobs of rock in place at frequent intervals show the rounded surfaces of *roches moutonnées*, but in most places no striae could be found. The surface is weathered rough, or broken up, as if by changes of temperature, into small fragments. Grooves are found at about 11,100 feet elevation on the left bank of the stream, with direction S. 43° W. In the bottom of the valley some areas are almost flat; at a few points in

the upper part small ponds occur. Two rock streams occur at from 12,000 to 12,500 feet in elevation. Talus slopes and precipitous cliffs beyond the talus mark the boundary of the cirquelike valley.

The tributary valley from the northwest has a bottom with rounded ledges; but the stream is in a deep canyon part of the way, first at a point more than halfway up the valley and again near its mouth. No striated rock surfaces were observed. In general, the slope of the bottom of the valley is very steep, and the sides are made up of long talus slopes with precipitous faces above them. At the upper end of the valley is an unusually fine example of a rock stream, which extends more than a quarter of a mile from the precipice which forms the head of the valley. In the lower part of the valley of this tributary on the west side, at an elevation of about 11,200 feet, is a small area of uneven, hummocky ground inclosing a pond 30 or 40 feet in diameter; this uneven topography is evidently due to landsliding.

At an elevation of about 10,300 feet, a precipitous cliff of the Telluride formation causes falls 100 feet or more in height in the streams both from the head of the main valley and from the branch coming from the northwest. Below the falls and down to about 9,900 feet in elevation there is much fragmental material in the stream bed, rock in place being visible only occasionally. At about 9,900 feet, the stream bed lies in a canyon cut in Dakota sandstone. Again at from 9,200 to 9,400 feet in elevation there are many bowlders along the stream. At most other places, the stream has its channel in bed rock or nearly so.

Park Basin is very similar in its main features to the valley tributary to Mill Creek from the northwest. It has a steep gradient where it joins the main valley, a grade less steep from 11,000 to 12,000 feet in elevation, steep talus slopes, and precipitous cliffs beyond the talus.

On the west side of the main stream at an elevation of from 10,000 to 10,200 feet, is an area of irregular, hummocky topography, in which are some small undrained basins. The material here is clay, with pebbles and bowlders, some of which are rounded. This area clearly lies within the limits of glaciation for this valley, but the uneven topography is no doubt due largely to landsliding.

On the west side of Mill Creek where it joins the valley of the San Miguel, a short, well-defined ridge extends south of west nearly to Eder Creek. Near its upper end its crest is about 500 feet above the bed of the stream (Mill Creek), and rapidly decreases in elevation toward the southwest. On the side of this ridge away from Mill Creek its slope is short, and joins, in its upper part, the unglaciated slope of the ridge lying between Mill Creek and Eder Creek; farther down it joins the glacial débris of the main (San Miguel) valley. No ridges transverse to Mill Creek appear in connection with the lateral moraine; either no terminal moraine was formed by the glacier occupying the valley of Mill Creek, or, if formed, it has been carried away.

Upstream from the lateral moraine just referred to, one-fourth to one-half a mile from where Mill Creek enters the San Miguel valley, there is an accumulation of glacial débris lying near the stream and up to about 9,400 feet in elevation. This accumulation forms what appears when viewed from the upstream side to be an irregular, narrow terrace whose top is not more than 100 to 150 feet above stream. Above the accumulation, the valley becomes slightly broader and for about one-fourth of a mile is sufficiently level to indicate that ponding of water with accompanying silting-up must have taken place. This more level surface is in sharp contrast with the steep slope on the same side of the stream near the San Miguel valley. On the east side of Mill Creek, no terrace appears corresponding to that on the west; some glacial débris is present, however. This deposit of drift at 9,300 to 9,400 feet in elevation is interpreted as a recessional moraine which for a time partially dammed the stream.

The maximum thickness of ice in the valley of Mill Creek was probably from 500 to 800 feet.

VALLEY OF CORNET CREEK

The head of this valley is a cirque with precipitous walls, steep talus slopes, a bottom showing some rock in place, some loose bowlders, and some finer fragmental material which in places supports a sufficient growth of low plants to conceal the rock fragments under a covering of green. The tributary valley from

the east, lying southwest of Mendota Peak, has much talus, a larger proportion of its area supporting vegetation, and lacks the high steep walls at its head which are characteristic of a typical cirque.

From timber line, about 11,000 feet in elevation, down to 10,200 feet, a considerable growth of trees, with the accompanying products of vegetable decay covering the ground, obscures the underlying rock in many places; a number of outcrops were found, however, yet no striae were seen.

On the east side of the valley, beginning at an elevation of about 10,200 feet and extending in a southerly direction for about one-fourth of a mile, is a distinct ridge composed, so far as could be observed, of clay, pebbles, and rounded bowlders, some of which are striated. This ridge begins just below a well-rounded ledge of the Telluride formation, and extends to the stream which joins Cornet Creek from the east on the 9,800-foot contour line.

The moraine lying across the lower part of the valley and forming part of the lateral moraine on the north side of the San Miguel valley has already been referred to. North of this moraine for nearly a mile the bottom of the valley has in most places a covering of glacial drift, part of which is stratified and part unstratified. On the west side of Cornet Creek opposite the moraine at 9,800 feet elevation, bowlders and other glacial débris lie as much as 100 feet higher than the top of the moraine on the east side. This fact probably has its explanation in the crowding-up of the glacier on the west side of Cornet Creek due to the ice coming from the valley of Bear Creek, a tributary which enters the San Miguel valley from the south at a point nearly a mile farther upstream than the valley of Cornet Creek.

The general shape of the different parts of the valley is typical of that usually found in the small, high, glaciated valleys of this region; that is, an upper portion comparatively broad and flat-bottomed, bounded by talus slopes and precipitous cliffs, and a lower part, narrower, with steep sides, gradually changing in shape of cross-section from U-shaped to V-shaped, as the tributary approaches the main stream. The maximum thickness of ice in the valley probably did not exceed 500 feet.

VALLEY OF MARSHALL CREEK

Marshall Creek drains Marshall basin and Middle basin, lying in the Telluride quadrangle, and Savage basin lying for the most part in the Silverton quadrangle. All these basins, as well as the valley of Marshall Creek below, are practically free from glacial débris; except for accumulations of talus and rock streams, rock in place is everywhere at the surface. *Roches moutonnées* occur at many points, and striae are abundant, their direction coinciding in general with the direction of the stream courses. Special illustrations of *roches moutonnées* may be mentioned as follows:

1. In the northwest part of Marshall basin, beginning at an elevation of 12,400 feet and including an area one-fourth of a mile square below that elevation, many *roches moutonnées* occur; striae within this area have directions varying from S. 25° E. to S. 35° E.

2. At an elevation of 11,300 feet on the north side of the road near the turn from northwest to west, two sets of striae are plainly marked; one set has direction S. 5° to 10° W.; the other set, not so deeply cut, about S. 45° W.

In the upper part of the basin the western slope is covered by a long talus slope, completely concealing the rock in place on that side. In the northeast part, at an elevation of from 12,500 to 12,800 feet, is a small rock stream.

In Middle basin a shallow lake occupies a rock basin; the outflowing stream passes through a channel about 10 feet deep. Northwest of the lake a ledge of rock in place 100 feet high shows *roches moutonnées*, but no striae. A little higher, at an elevation of nearly 11,700 feet, in both the east and the west branches of Middle basin rock streams are found extending from the base of the talus slopes which lie at the foot of the precipitous bounding walls of the valley. These rock streams are of two periods; the more recent are composed of fragments fresh in appearance, angular, and bare except for lichens on some of the surfaces. The older lie at the lower or outer edge of the more recent, the rock fragments are much disintegrated, so that the crests of the ridges are less sharp, and soil enough has accumulated to support vegetation, making the surface appearance that of rounded, green hills instead of bare ridges of angular fragments.

In Savage basin above 12,000 feet in elevation, there are found usually rock streams, and talus slopes at the bases of the precipitous bounding walls; below this elevation, as in the case of Marshall and Middle basins, there is usually a rock floor with *roches moutonnées* and numerous striae; unlike Marshall basin, however, Savage basin has a number of small rock basins, some of which contain water. The rock streams here are of two periods, as is the case in Middle basin, and the arrangement of the two with respect to each other is likewise for the most part the same, that is, the older lying as a narrow belt outside or below the more recent. In a few places, however, the older, more rounded slopes are farther up the valley than those made up of bare, angular rock fragments; this seems to be due to the movement of the fragments transported in more recent time around the older deposit, much in the way that a glacier is seen to move around an island or a promontory of rock which is a little too large to be overridden.

The maximum thickness of ice for the area drained by Marshall Creek was probably about 800 feet.

VALLEY OF INGRAM CREEK

The greater part of the area drained by Ingram Creek lies in the Silverton quadrangle. The north branch of the basin has but few good examples of *roches moutonnées*, though many projecting points and ledges are distinctly rounded. Striae bearing S. 88° W. occur on the east side of the stream at an elevation of 12,000 feet. In the upper part of the north branch are the usual precipitous bounding walls, talus slopes, and rock streams of two different periods.

The central subdivision of the basin is deeply carved. Channels up to 100 feet wide and 50 feet deep occur in the bed rock, approximately parallel to the length of the valley; the sides of these channels are precipitous, and in many places well smoothed. Striae in general parallel to the course of the stream are abundant. Talus slopes are found at the north side and the east end.

The south branch has many *roches moutonnées;* some of the surfaces are striated, some are weathered rough. Ice passed over the 12,400-foot ridge situated between the central and south

branches of the basin. In the southeast part of the south branch the *roches moutonnées* forming the bottom of the basin are not more than 300 feet lower than the steep-sided ridge which forms the divide between Ingram basin and Mineral basin; it is therefore believed that the upper surface of the glaciers occupying these two basins was continuous at the time of the maximum extent of ice in the more recent epoch of glaciation.

The lower part of the course of Ingram Creek as named on the Telluride topographic sheet is an extension of the upper part of the valley of the San Miguel River. From about 11,000 feet in elevation, the stream descends in a series of falls and cataracts to its junction with Bridal Veil Creek, a total fall of over 1,500 feet in about seven-tenths of a mile. Immediately above elevation 11,000 feet, the valley has the U-shaped cross-section. At a higher elevation it assumes the form common to the high glaciated valleys in this region. The maximum thickness of ice in this valley was probably about 500 feet.

ON THE STRATIGRAPHIC POSITION AND AGE OF THE JUDITH RIVER FORMATION

A. C. PEALE[1]

For some years there has been a suspicion in the mind of the writer that perhaps, after all, the older geologists were correct in their views as to the position of the Judith River beds in their relation to the previously recognized, undisputed Fort Union formation, i.e., that the Judith River beds were immediately below the Fort Union formation. This view was strengthened when, in 1909, plants of undoubted Fort Union age were brought in from supposed "Judith River beds" on Big Sandy Creek, about fifty miles northwest of the mouth of the Judith River, by members of the U.S. Geological Survey, and confirmed upon a careful study and review of the evidence furnished by stratigraphic, vertebrate, and invertebrate data as detailed by Stanton and Hatcher in their work[2] and by Dr. O. P. Hay's paper "Where Do the Lance Creek (Ceratops) Beds Belong?"[3] It is the purpose of the present paper to show that the Judith River beds are of Eocene-Tertiary age, and not of Belly River (Cretaceous) age, and are to be correlated with the Lower or somber portion of the Fort Union formation as defined and described by Knowlton,[4] now known as the Lance formation.

Nearly forty years ago, or, to be more exact, in 1875,[5] the writer, in attempting to correlate the Cretaceous and Tertiary formations in connection with work of the Hayden Survey in Colorado, took up the consideration of the Judith River beds, and among other

[1] Published by permission of the secretary of the Smithsonian Institution.

[2] *Bull. U.S. Geol. Surv., No. 257*, 1905.

[3] *Proc. Indiana Acad. Sci.*, Twenty-fifth Anniversary Meeting, 1909.

[4] The "Stratigraphic relation and paleontology of the 'Hell Creek beds,' 'Ceratops beds,' and equivalents, and their relation to the Fort Union formation."—*Proc. Wash. Acad. Sci.*, XI, No. 3, pp. 179–238.

[5] *U.S. Geol. and Geog. Surv. Terr., 1874*, Washington, 1875, pp 154, 155.

conclusions, made the statement that the Judith River beds lie immediately below the Fort Union (as then known), and have their equivalent in Colorado, occupying there the same position as in Montana. He also stated that he believed them to be of Cretaceous age, and thought that they formed either the upper part of the Fox Hills, or a group to be called No. 6, the Fox Hills being known as No. 5.

This opinion as to the Cretaceous age of the beds was based upon the study of the vertebrates by Professor E. D. Cope, a position which has been taken by all vertebrate paleontologists, both in the United States and in Canada. From this opinion the writer, in the light of what is known today, which will be briefly detailed below, dissents, and wishes to express here the conviction that the Judith River beds are of Eocene age. He, however, holds to his previous view that they do lie between the Fox Hills and the Fort Union formations as then known and described. This is why they were so generally referred to the Laramie. This is the position that has been assigned them by everyone who has studied them from the time they were first noted by Hayden in 1853–55, and named by him in 1871, down to the time of the investigations by Hatcher, who was the first (in 1902)[1] to assign them to a position in the Montana Cretaceous lower than that of the Fox Hills. In 1896, however, Hatcher had considered the Judith River beds as representing the lower 400 feet of strata at the base of the Ceratops beds of Converse County, Wyo., and just above the Fox Hills sandstone. This position above the Fox Hills coincides with that assigned them by Hayden, Meek, Cope, and Osborne, and by the writer, as just stated. The position indicated for the beds by Hatcher, in 1902,[2] is that assigned them by Stanton and Hatcher in 1905, and their views are fully elaborated in their bulletin[3] published by the U.S. Geological Survey.

The historical aspect of this question has been so thoroughly and most admirably stated by Stanton and Hatcher in the bulletin just cited, and it is only necessary to recapitulate enough to show that the statement made above is correct.

[1] *Science*, XVI, 831, 2.

[2] *Ibid.*, XVIII, 211.

[3] *Bull. U.S. Geol. Surv., No. 257*, 1905.

In 1861 Meek and Hayden, after referring to the early conflicting views as to the age of the Judith River beds, say:[1] "They are really of Tertiary age, and hold a position at the base of the great lignite series [Fort Union formation] of the northwest." In 1871[2] Hayden gave these deposits the name "Judith group," and says:

> The sediments do not differ materially from those of the Fort Union group, and they contain impure beds of lignite, fresh-water mollusca, and a few leaves of deciduous trees. But the most remarkable feature of this group is the number and variety of the curious reptilian remains of which we have only yet caught a glimpse.

As to the age of the underlying sandstones near the mouth of the Judith River, concerning which there had previously been some doubt, both Meek[3] and Hayden[4] in 1875, independently of each other, correlated them with the Fox Hills, Meek saying that "we cannot be far wrong in regarding the latter beds [the marine Cretaceous beds at the mouth of Judith River] as holding a position at the horizon of the top of the Fox Hills." Cope,[5] in 1874, in a "review of the vertebrata of the Cretaceous period found west of the Mississippi River," in a notice of the Judith River beds under the head of the Fort Union or lignite group, says: "From the standpoint of the writer, these beds would be at the top of the Cretaceous and more or less related to the Fort Union epoch." After the early explorations by Hayden, the first geological examination of the Judith River country was made by Edward S. Dana and George B. Grinnell[6] in the summer of 1875. They made a short excursion to the mouth of the Judith River and spent two days in this locality. They speak of their results being, of course, meager. "Enough,[7] however, was seen to establish the age of the beds at this point as beyond a doubt Cretaceous, three members of this division of Meso-

[1] *Proc. Acad. Nat. Sci.*, 1861, p. 415, footnote.

[2] F. E. Hayden, *Preliminary Report, U.S. Geol. Surv. Wyoming*, Washington, 1871, p. 97.

[3] *Bull. U.S. Geol. and Geog. Surv.*, I, 2d series, No. 1, p. 39.

[4] *Ibid.*, p. 403.

[5] *Bull. U.S. Geol. and Geog. Surv., 1874–75*, I (1875), 1st series, p. 6.

[6] Geological report in Ludlow's report of a *Reconnaissance from Carroll, Montana, on the Upper Missouri, to the Yellowstone National Park and Return*, Washington, 1876.

[7] *Ibid.*, p. 124.

zoic time having been found there and identified by fossils." The three members referred to were No. 4, Fort Pierre, No. 5, Fox Hills, and No. 6, Fort Union. The thickness of the latter was estimated at 400 feet, and the strata are described as beds of white sandstone containing occasional layers of a clayey brown sand rock, "at the mouth of the Judith River, evidently overlying the beds of No. 5 [Fox Hills] before referred to." From these beds they obtained the vertebrae and long neck bones of dinosaurs identified by Professor Marsh as belonging very near the genus *Hadrosaurus* [Trachodon] of Leidy. With these remains were found Unios and, in some layers, a little lignite, the general association seeming to refer the deposits to the Fort Union beds.

Professor E. D. Cope was the next to visit the region. In the summer of 1876 he explored the region near the mouth of the Judith River and eastward as far as Armel's Creek, 130 to 150 miles to the eastward from Fort Benton. He fully corroborated Hayden's observations and his sections are substantially the same. He regarded the Judith River beds as Cretaceous, with Tertiary affinities,[1] and referring to their position, says:[2] "In the Judith region the relation of the Fox Hills sandstone to the superincumbent strata is everywhere observable." "The ferruginous, soft sandstone of the Fox Hills group is everywhere the line of demarkation between the black shales of No. 4 [Fort Pierre] below and the Judith River beds above."[3]

The last identification of fossils made by Professor F. B. Meek was for Professor Cope. The fossils were *Inoceramus barabini*, *Inoceramus* sp.; and *Baculites compressus*, and were obtained by Cope[4] from the black shales of No. 4. Although Meek had not revisited this region, his last word on the Judith River beds is interesting and illuminating.[5] Basing his opinion upon the invertebrates found in the beds immediately underlying the Judith River beds near the mouth of the Judith River, he correlates them with the upper part of the Fox Hills.[6] As to the Judith River group,

[1] *Bull. U.S. Geol. and Geog. Surv.*, III (1877), 569.

[2] *Ibid.*, p. 568. [3] *Ibid.* [4] *Ibid.*

[5] *Report of U.S. Geol. Surv. Terr.*, IX (1876).

[6] *Ibid.*, p. xxxvi.

which he believes to be somewhat extended in the upper Missouri River region at the base of the Fort Union group, he suggests the probability of its Cretaceous age, but says: "Yet this can scarcely be properly regarded as an established fact,"[1] and then refers to the mingling of the Eocene and Cretaceous types of vertebrates in the beds.

During the summer of 1882 Dr. C. A. White[2] made a special study of the geology about Fort Union and the region extending thence up the Yellowstone. He ascertained as the result of this study that, with the exception of one or two small exposures of the Fox Hills lying immediately below the Fort Union [which he referred to the Laramie], the latter occupied the whole region and from the beds so referred the collected fossil plants, fresh-water invertebrates, and dinosaurian remains, and states that the latter are found toward the base [that is, in the beds since referred to the Lance formation].

The following year Dr. White[3] spent part of the months of July and August in the area between Fort Benton and Judith River and the Highwood Mountains studying the relations of the Laramie [Lance?] group to the underlying formations. He was joined here by Professor L. F. Ward[4] and on August 22 they began the descent of the Missouri from Fort Benton to Bismarck, which they reached September 21. Ward says that the most notable fossil plant locality discovered was about 7 miles below Coal Banks on the right bank of the Missouri River, occupying a stratigraphic position near the base of the Fox Hills, probably in the Fort Pierre group. These were of special interest as being the only Cretaceous fossil plants found up to that time in the United States above the Dakota group. White and Ward as the result of this trip saw no reason to differ with the latest conclusions of Meek and Hayden, or those of Cope, but, as Dr. Stanton[5] says, their stratigraphic observations were never fully published. Later, White[6] in dis-

[1] *Ibid.*, p. l–li.

[2] *Am. Jour. Sci.*, 3d ser., xxvii (1883), 121.

[3] *Fifth Ann. Rept. U.S. Geol. Surv. for 1883–84–85*, p. 50.

[4] *Ibid.*, p. 60.

[5] *Bull. U.S. Geol. Surv. No. 257*, p. 27.

[6] *Ibid., No. 82*, pp. 174–77.

cussing the Belly River formation, refers to the identity or close resemblance between the Belly River beds and the fresh-water Laramie [Lance] (which included at that time the Judith River beds) and suggests the gradual coming-in of the Belly River series between the Colorado and Montana, and the gradual thinning-out of the Montana until the Laramie [Lance] occurs, resting immediately upon the Belly River, the two blending, with the Montana absent. He says, however: "It is true that no observation has yet been made of a complete thinning-out of the Belly River formation in any direction, nor of its blending with the Laramie [Lance] by the absence or by the thinning-out of the Montana formation."[1]

Dr. White[2] recognized the fact that both the Belly River series and the Laramie [which as he used it included the Lance and the Judith River beds] rest upon marine Cretaceous and says also: "Unlike the Laramie [Lance], the Belly River formation is immediately overlain, as well as underlain by marine Cretaceous strata." The latter he says are undoubtedly referable to the Montana formation. He says further:[3] "What gives this formation [Belly River] especial interest is the intimate relation of its fauna and flora to those of the Laramie [Lance], although these two non-marine formations are, in the district within which both are now known to occur, separated by a great thickness of strata which are unmistakably of marine origin." Although Sir J. W. Dawson[4] has stated that the flora of the Belly River series very closely resembles that of the Lower Laramie [Lance] we shall see later on that such resemblance as exists is not very striking. In regard to the survival of the molluscan fauna he concludes that "the fresh-water habitat of the Belly River molluscan fauna was shifted by subsidence and gradual filling of aqueous areas."

In 1894 Dr. Stanton spent a few days with Mr. W. H. Weed near the mouth of Judith River. They traveled by rowboat down the Missouri River from Fort Benton to Judith, passing over and studying the formations underlying the Judith River beds, beginning with Fort Benton shales. Dr. Stanton confirmed the statements of previous observers that some of the strata beneath the Judith River beds contain a fauna that is elsewhere characteristic of the

[1] *Bull. U. S. Geol. Surv., No. 257*, p. 176. [2] *Ibid.*, p. 174. [3] *Op. cit.*, p. 175.
[4] *Trans. Roy. Soc. Canada*, III, sec. IV (1885), p. 20.

Montana group, or Fort Pierre and Fox Hills formations. He was especially impressed by the occurrence, in the upper part of these underlying beds, of a zone containing *Cardium speciosum*, *Mactra alta*, *Tancredia americana*, and other forms which in north-central Colorado are known to occur only in the Fox Hills beds immediately beneath the Laramie. No beds higher than the Judith River were seen, and the view was adopted that the Judith River series overlies all of the Montana group and is referable to the Laramie. When a few days later the overlying marine Cretaceous shales were seen in contact with upturned Judith River beds near Havre, Mont., their apparent position was supposed to be due to faulting, of which there was abundant evidence in the neighborhood.[1]

As a result of this work Dr. Stanton[2] gave Mr. Whitman Cross the following section made in Dog Creek, published in 1896:

The fresh-water Judith River beds are well exposed in bluffs on Dog Creek, 4 or 5 miles from the mouth of Judith River, and also on the north side of the Missouri within 3 or 4 miles of the same place. The section in this neighborhood shows about 650 feet of marine Cretaceous strata overlain by 300 to 350 feet of fresh-water beds. The succession of strata and thickness as estimated by Mr. W. H. Weed are as follows, beginning at the base:

1. Soft, dark clay shales.
2. Band of ferruginous sandstone with *Avicula linguiformis*, *Inoceramus cripsii*, *Baroda wyomingensis*, *Placenticeras placenta*, etc.
3. Shales like No. 1.
4. Coarse gray laminated sandstone.
5. Carbonaceous shales with bed of lignite at base..... 100
6. Brown sandstone with great numbers of *Cardium speciosum* and a few other species..... 30
7. Sandy shales..... 25
8. Dark clay shales with concretions containing *Baculites ovatus* in lower portion and sandy bands and concretions near the top with a characteristic Fox Hills fauna including:

Nucula sp.	Liopistha (Cymella) undata
Clisocolus cordatus	Pholadomya subventricosa
Callista nebrascensis	Mactra formosa
Tellina aequilateralis	Lunatia subcrassa
Tancredia americana	Baculites ovatus

The total thickness of this bed was not seen at any one place, but it is at least 350 feet.

Immediately above these dark shales is a bed of greenish-yellow sandstone which occasionally forms bluff exposures 50 or 60 feet high, but usually only slightly exposed in steep slopes and largely covered by wash from the softer and lighter-colored beds above. This was taken as the dividing line between

[1] Stanton and Hatcher, *Bull. U.S. Geol. Surv., No. 257*, 1905, p. 10.

[2] *Monographs U.S. Geol. Surv.*, XXVII (1896), 239–41.

the marine and fresh-water beds, though no fossils excepting silicified wood were found in the lower 200 feet of the latter. The remainder of the section, about 300 feet in thickness, is apparently conformable with the underlying beds, but is quite distinct from them in color and texture. It consists of alternations of light-colored, soft, friable sandstones, clays, and marls, with some seams of lignite and purplish carbonaceous bands. Fossils are abundant in the upper 200 feet, consisting of fragments of silicified wood, bones, and numerous invertebrates. The latter include the following species:

Sphaerium recticardinale	Goniobasis sublaevis
Sphaerium planum	Goniobasis subtortuosa
Unio danae	Goniobasis sp. closely related to G. tenuicarinata
Unio cryptorhynchus	
Anodonta propatoris	Campeloma vetula
Viviparus conradi	Vetrina ? obliqua
Helix veternus	Physa copei

At the top of the exposure above these fresh-water beds there is a band of brackish-water fossils, reported by both Meek and Hayden and by Cope, which contain *Ostrea subtrigonalis*, *Anomia* sp., *Corbicula occidentalis*, *Corbula cytheriformis*, *Goniobasis convexa*, etc. This band was not seen by me in the neighborhood of Judith River, but I afterward saw it near Havre, Mont., holding the same position above the fresh-water beds.

Cross, in commenting on this section, refers to the specific identity of the brackish-water shells found by Stanton on Dog Creek and near Havre with those found by Weed in the Livingston[1] beds, saying their presence does not indicate the Laramie (by which he means true Laramie as found in Colorado) age of the Judith River beds, and as to the apparent conformity with the Fox Hills urges for the Judith River beds the same considerations as he did in discussing the Converse County beds (now called the Lance) in Wyoming. These as given on p. 236 are as follows:

> There are many places in the West where the section of visible sedimentary formations from the Cambrian to the Cretaceous seems a conformable one, and it has frequently been spoken of as such, but the researches of the last two decades have proven the existence of many important stratigraphic breaks in this series, which are in certain places shown as great unconformities but cannot be identified at other points. Especially in the plains country adjacent to the Rocky Mountains conformity of formations cannot be assumed to prove continuity of sedimentation. The visible conformity between the Ceratops

[1] The Livingston age of these beds was afterward denied by Dr. Stanton and others, but the point the writer wishes to make here relates more especially to the unconformity.

beds and the Fox Hills in Converse County cannot be accepted, contrary to other evidence, as proving the former to have been deposited in the epoch next succeeding the Fox Hills.

It is apparent from what has been quoted above that Dr. Stanton, when he went with Weed in 1894 from Fort Benton to the Judith River, found the Judith River beds in the type region in their normal position and that he was correct in assigning them to the stratigraphic position immediately overlying the Montana formation which, in its upper portions, contained a Fort Pierre and Fox Hills fauna. It was only when he got into the disturbed region near Havre, Mont., that he found marine Cretaceous shales overlying what he called "Judith River beds" and his explanation, that their apparent position *when so found* was due to faulting, was probably also correct.[1] Of course these beds exposed at Havre were not the real Judith River but the true Belly River series which normally underlies the Pierre as exposed in Canada north of this region. These beds were again examined by Dr. Stanton when with Hatcher in 1903. Their field studies were begun at this point, Milk River at Havre, and they

> examined the excellent exposures along that stream to the international boundary, and beyond to Pendant d'Oreille Police Barracks, which is near one of Dawson's described localities, where the base of the Belly River beds is seen resting on the marine "lower dark shales." This is near Lake Pakowki of the maps, locally known as "Badwater Lake." We also examined the exposures of upper Belly River beds showing contact with the overlying "Pierre shales" on Sage Creek, Canada, as described by Dawson and McConnell, and continued our observations as far north as the Cypress Hills, where the top of the overlying marine Cretaceous is seen. Passing down Milk River below and around the eastern end of the Bearpaw Mountains to Cow Creek and the Missouri River at Cow Island and thence up Dog Creek, Judith, and Eagle Creek, Mont., we have studied the typical areas of the Judith River beds described by Meek and Hayden, and of the Eagle formation described by Weed. . . . .
>
> We have become fully convinced that the Belly River beds are identical with the Judith River beds, as Dawson long ago suggested. Our conclusion

[1] Dr. Stanton's exact words are as follows: "When a few days later the overlying marine cretaceous shales were seen in contact with upturned Judith River beds near Havre, Montana, their apparent position was supposed to be due to faulting of which there was abundant evidence in the neighborhood."—*U.S. Geol. Surv. Bull., No. 257*, p. 10.

is based on lithologic character, stratigraphic sequence, the vertebrate and invertebrate faunas of the beds themselves, as well as on the paleontology of the underlying and overlying beds in both Canada and Montana.[1]

In discussing in another place[2] the areas in which Judith River beds occur, Stanton and Hatcher refer to the exposures near Havre, the eastward extent of which they did not determine, and say:

> It is very *probable* that this area is connected with the Cow Creek area by almost continuous exposures across the divide separating the drainage of the Missouri from that of Milk River east of the Bearpaw Mountains. On our journey from Havre to Cow Creek we passed through the eastern foothills of these mountains and crossed several areas of igneous rocks, but on Bean Creek near Lloyd post-office we saw outcrops apparently belonging to the Judith River beds, and *if our route had been a few miles farther east we could probably have had the formation in sight all the time.*[3]

This statement is a pure assumption, for it is evident that the beds were not traced continuously from the Milk River area to the vicinity of Cow Creek on the Missouri River, and the probabilities are that in this region to the eastward the distinction between the Belly River and the Judith River formations and not their identity would have been clearly shown. It is more than probable that here is the point where the supposed correlation fails. The Belly River, the Judith River, the Lance, and the Fort Union formations all have their representatives in this area, which is one of great disturbance due to faulting and the occurrence of volcanic intrusions. The lithological resemblance between the strata of these formations has been noted by all who have seen them, not only in this region, but to the southward and also northward in Canada. The relations of the beds in this disturbed area will be determined only after a most careful investigation of the country surrounding the Bearpaw Mountains, extending far enough away from the mountains to give normal undisturbed sections which can be closely studied. A careful stratigraphic tracing of these beds in the undisturbed region, which cannot be made in a flying trip across the country, will also be necessary, together with accurate paleontologic collections and their careful study.

[1] *Science*, N.S., XVIII (1903), 211–12.

[2] *Bull. U.S. Geol. Surv. No. 257*, 1905, p. 61.

[3] The italics in this quotation are those of the present writer.

Study by Hatcher of the vertebrate collections made by him in 1882 and 1883 from the Judith River beds led him to the conclusion that this vertebrate fauna was older than Laramie fauna of the uppermost Cretaceous. By Laramie as used by Hatcher, it must be remembered, is meant the Ceratops beds, now called the Lance formation, which in the writer's opinion has been conclusively shown by Knowlton[1] to be of Lower Fort Union (Eocene) age. Hatcher was confirmed in his views by finding marine Cretaceous shales apparently overlying the Judith River beds. It must be again recalled in this connection that this was an area of complicated folding and great disturbances, the result mainly of numerous faults recognized by all who have been in the region from the time of Hayden's first explorations to those of Hatcher and Stanton. The latter says:[2]

"No better description of the frequency of these disturbances and the difficulties they have caused the stratigrapher can be given than that of Dr. Hayden," whom he quotes. The latter part of this quotation is as follows: "So much are the beds disturbed by forces acting from beneath that it seems almost hopeless to obtain a section showing with perfect accuracy the order of superposition of the different strata."

In 1896 Hatcher made the statement that the Judith River beds were certainly older than the Ceratops beds of Converse County, Wyo., and that "the dinosaurs from the Judith River country belonged to smaller and less specialized forms than those from the latter locality," and refers in the same article to his belief that "the Judith River beds are the equivalent of the 400 feet of barren sandstones, thus lying between the base of the Ceratops beds and the marine Fox Hills sandstones in Converse County, Wyo." Later, he repeats[3] this statement and adds: "I am at present of the opinion that they pertain to a still lower horizon."

In the early part of 1903 Hatcher says he "believes the exact stratigraphical position of the Judith River beds remains unsettled and that it is premature to assert that the true Judith River beds

[1] Knowlton, *Proc. Wash. Acad. Sci.*, XI (1909), No. 3, pp. 179–238; and *Jour. Geol.*, XIX (May–June, 1911), 358–76.

[2] *Bull. U.S. Geol. Surv. No. 257*, 1905, p. 34.

[3] *Science*, N.S., XVI (November 21, 1902), 832.

certainly overlie the Fort Pierre and are of more recent age, although this is now very generally believed and may eventually prove to be the case."[1]

During the summer of 1903 Mr. Hatcher and Dr. Stanton spent two months in the field study of the Judith River formation; part of the time in the Judith basin. The results of their investigations were published in *Bulletin of the U.S. Geological Survey No. 257*, 1905. In a preliminary statement published in August, 1903,[2] they restate their belief that the Judith River beds occupy a lower position than had usually been assigned them and give a summarized section which divides the Montana into four formations in ascending order as follows: Eagle formation, Claggett formation, Judith River beds, and Bearpaw shales. As to the beds which are supposed to overlie the Judith River beds and for which the name Bearpaw shales is proposed they say:

> They have the lithologic and faunal characters of the typical Pierre but represent only a fraction of that formation as usually understood. Beneath the light-colored mostly non-marine Judith River beds, is another formation 400 feet in thickness, which in its lower half resembles the Bearpaw shales and yields a few of the same species of fossils. Its upper 200 feet, however, contain several sandstone beds which bear a fauna that has hitherto been called "Fox Hills." We propose the name *Claggett formation* for these shales and sandstones underlying the Judith River beds.

Having in mind the possibility, if not the great probability, that the two series of beds, Belly River, and the Judith River with which the former was correlated by Stanton and Hatcher, were not one and the same, but were entirely distinct formations, and that the latter is really the equivalent of the division of the Fort Union to which the name Lance has been applied by the U.S. Geological Survey, the writer decided to visit the area in which the typical Judith River beds are exposed, and in accordance with this decision the month of July, 1911, was spent in this area in company with Mr. A. C. Silberling, formerly connected with the Carnegie Institute of Pittsburgh, and Professor G. L. Wait, of the Lewistown

[1] *Science, N.S.*, XVIII (March, 1903), 472.

[2] *Ibid.*, (August 14, 1903), 211, 212. The article was sent in from the field from Judith Mountain.

High School, whose familiarity with Fergus County, Mont., was of the greatest assistance in the work. Knowing from the work of Stanton and Hatcher that the area north of the Missouri River and around the Bearpaw Mountains was one complicated in its geological structure by numerous faults and folds and areas of intrusive rocks, it was decided to begin the section far enough south so that if possible there might be no chance of error due to the occurrence of folding or faulting. We therefore followed the road leading a little west of north from Lewistown between the North and South Moccasin mountains to Deerfield, from which point we turned westward, reaching the Judith River about 40 miles above its mouth. This part of our course led us over the shales of the Colorado, as mapped by Calvert,[1] with a few outcrops of the underlying Kootenai formation showing on either side of the lower slopes of the Moccasins. The Colorado shales are well shown at Stough's ranch, having a thickness of about 1,000 feet overlaid by a sandstone referred to the Eagle. This is a massive white sandstone not over 100 feet in thickness in most places. As followed laterally it fades out into a yellowish sandstone which is somewhat shaly. This sandstone caps the bluffs on either side of Judith River, contrasting strongly with the underlying dark shales of the Colorado. Above it is an alternating series of massive yellowish sandstone and shaly beds reaching a total thickness of about 200 feet. A coal mine is worked in these upper sandstones about 2 or 3 miles east of the valley of the Judith River.

Above these supposed Eagle sandstones the beds are softer sandstones broken down and mainly covered. They are several hundred feet in thickness and undoubtedly represent the Belly River interval, but the outcrops were too meager to determine much in detail about them.

The dark-colored shales of the Pierre resting on these sandstones form the surface of the bench beginning several miles to the eastward of the coal mine, and the road to Kendall passes over them, several good outcrops showing, especially to the north of the road, but they do not show on the Judith south of the mouth of Warm Spring Creek. However, the Pierre shales appear in the

[1] "Geology of Lewistown Coal Field," *Bull. U.S. Geol. Surv. No. 390*, map.

valley long before Fullerton is reached and at the latter place form the bluffs on both sides of Judith River in typical exposures containing characteristic fossils. The entire thickness does not show at Fullerton but there is here an exposure of at least 400 feet. The total thickness is probably from 600 to 900 feet. Immediately below the Judith River beds which form the summit of the bluffs and the surface of the bench reaching to the eastward, there are from 50 to 100 feet of sandstone with *Halymenites major* and the following invertebrate fossils: *Avicula nebrascana* E. & S., *Tancredia americana* M. & H., *Lunatia subcrassa* M. & H., *Tellina equilateralis* M. & H., and *Mactra* sp. These are identified by Dr. Stanton and referred by him to the Claggett, but it seems to me they are undoubtedly of Fox Hills age, the beds containing them resting on Pierre shales and being immediately followed above by the Judith River beds. The basal layers of the latter series contain *Ostrea subtrigonalis* and other brackish-water forms. The contact between the two formations as seen from the west side of the valley is somewhat irregular, suggesting the unconformity which elsewhere marks the upper limit of the Fox Hills and the base of the Lance formation. Up to this point no faults occur nor is there any evidence of folding nor of overturn. The section is normal and complete, unless a stratigraphic break exists corresponding to the paleontological hiatus at the top of the Fox Hills, the sequence from the Kootenai up through the Colorado and Montana into the Judith River formation being perfect except for the paleontologic and possibly stratigraphic hiatus at the base of the latter.

A short distance below Fullerton the first of three well-marked faults that occur south of Judith Landing crosses Judith River. The direction of this fault is nearly east and west and the dip of the beds thrown down is quite steep (about 20°) toward the northwest. This outcrop, mainly of Fox Hills sandstone and a smaller part of Judith River beds, is underlain by Pierre shales; and above the faulted beds are Pierre shales capped by Fox Hills sandstones (containing invertebrates and *Halymenites major*) which underlie the undisturbed Judith River beds which have a very slight inclination to the north or northwest. The lower slopes of the hill back to the faulted beds is composed of Pierre shales capped with Fox

Hills sandstones and overlying Judith River beds. This fault-line was afterward crossed twelve miles to the eastward near the crossing of Dog Creek. The second fault-line parallel to this one is exactly like the first, but the third one, a few miles south of Judith Landing, is a block fault of Fox Hills sandstones with a steep dip on the southwest side. From Judith Landing a trip up Dog Creek for about three miles above its mouth was taken to the point visited by Stanton and Hatcher and here another fault similar to those just referred to was seen showing, not only on Dog Creek, but extending across to the north side of the Missouri River. Lack of time prevented a tracing of these lines, and also precluded the close examination of the complicated conditions shown on Dog Creek.

That the structure is complicated is shown by the following conditions. In Plate 2, opposite p. 36, of *Bulletin No. 257* of the Geological Survey is shown a cliff of sandstone referred by Dr. Stanton to the Upper Eagle, which was found by him to be very fossiliferous, containing the following forms: *Cardium speciosum*, *Tellina montanensis*, *Baroda* sp., *Callista* sp. Cf. *C. deweyi*, *Mactra alta*, *Mactra formosa*, *Lunatia subcrassa*. This cliff was visited by us in July, 1911, and in horizontal beds lying below this cliff the following vertebrate remains were collected: *Champsosaurus* vertebrae, carnivorous dinosaur tooth, *Paleoscincus* tooth, Crocodile teeth, *Brachychampsa* (?) tooth, ganoid fish remains, and shark's teeth. These were identified by Mr. C. W. Gilmore of the U.S. National Museum, who says: "All of these forms may be found either in Judith River or the Lance formation with the possible exception of *Brachychampsa*, which at this time has been recognized only at Hell Creek and in the Ceratops beds of Wyoming." In the same series of beds 400 feet *higher* the following were found: carnivorous dinosaur tooth, a small ceratopsian tooth, *Trachodon* tooth, a turtle (not determinable), a crocodile (probably *Leidyosuchus*) and remains of a ganoid fish and shark's teeth. Below the lower of these two fossiliferous beds (both of which are regarded as of Judith River age) in beds standing almost on end the following invertebrates were obtained, viz., *Avicula nebrascana* E.&S., *Tancredia americana* M.&H., *Tellina equilateralis* M.&H., *Mactra* sp., *Lunatia subcrassa* M.&H., *Cardium speciosum* M.&H.,

Mactra formosa M. & H. These have been identified by Dr. Stanton, who says: "This lot is apparently made up of collections from two distinct horizons. The first five species of the list are from the upper half of the Claggett, the other two probably from a lower bed which may also be in the Claggett or possibly as low as the Eagle."

There is no mixing of horizons *stratigraphically*, as all of these specimens collected by the writer came from an area that can be included within one's outstretched arms, in which the exposure is perfectly shown; therefore they are *all* from the Claggett of Dr. Stanton, or, according to the writer, from the Fox Hills formation, as the species are found in the Fox Hills of Colorado and other portions of the Rocky Mountains. The fact that two of the species are mentioned as "possibly" of Eagle age and these two rather widely distributed in the Fox Hills raises the question as to whether the sandstones occurring so frequently along the Missouri River and supposed to be brought to the surface by faulting may not be of Fox Hills age rather than of Eagle age, especially as lithologically they are almost indistinguishable. It was impossible, as already intimated, to unravel the structure here in the few hours we spent at this locality.

Returning to Fullerton we crossed the county to the eastward, the surface formation until we reached Dog Creek being the beds of the Judith River formation. East of Dog Creek the faulting was again in evidence, beds of Pierre and Judith River age mainly being involved, although it may be found later that the Eagle sandstones and Belly River formation are present in some of the ridges. So much of the surface of this area is covered and the lines of the faulting so numerous (there being at least six of them separated by areas of Pierre shales) that no attempt was made to unravel the complicated structure. Until a complete areal survey is made, the structure here must remain obscure. At Mauland (now known as Boe's ranch), which is about 10 miles south of the Missouri and about 20 miles east of Dog Creek, well-marked exposures of Judith River, as determined by fragments of vertebrate remains, were seen at the ranch dipping steeply (20° to 25°) against a fault-line, separating them from the Pierre shales, which are

almost horizontal in this immediate place but only a short distance away are seen to dip gently toward the north or northwest beneath the supposed Judith River beds which cap the ridge. The relations of the Pierre and overlying Fox Hills in the latter outcrop were plainly seen, as they dip normally beneath the Judith River beds.

From this point we turned back toward Dog Creek, crossing it about eight or ten miles farther south than our crossing on the way eastward, and thence we returned to Lewistown. The principal result of this trip was the determination of the geological position of the true Judith River beds to be above the Fox Hills, verifying Stanton's observations of 1894, and confirming his original opinion that when the Fort Pierre shales—or, as he renamed them, Bearpaw shales—appear to lie above the *Judith River beds* it is due to faulting.

It was determined to examine next the supposed Judith River exposures in other areas mentioned by Stanton and Hatcher. Here again we went to the southward to avoid the complicated region about Bearpaw Mountains, especially as lack of time prevented our going northward to and beyond the Canadian line. The areas in Assiniboia are, according to the Canadian reports, of undoubted Belly River age, as described first by Dr. G. M. Dawson.[1] These beds were traced by Stanton and Hatcher to the vicinity of Havre, Mont., where they lie beneath Pierre shales without any unconformity or faulting. The first area visited by us was that on Fish Creek in which the section was gone over from the Jurassic up through the Cretaceous to the Fort Union. This section is essentially the same as that given by Douglas[2] and subsequently examined by Fisher. However, instead of finding Laramie resting on the Fox Hills, in which the characteristic *Halymenites* occurs, the beds lying immediately above were found to be of Livingston age with a typical flora, and between them and the undisputed Fort Union are good exposures of the Lance formation. It is, however, in the lower portion of the section that we are most interested. It is possible, as Fisher suggests, that the beds referred by Douglas to the Jurassic may belong to the Kootenai, as there is

[1] *Geol. Surv. Canada, 1882–84*, p. 116c.

[2] *Proc. Am. Phil. Soc.*, XLI, 207–24.

a lithological resemblance, but no fossils were found to prove this[1] supposition.

In these supposed Jurassic beds Douglas secured bones of a large dinosaur, above which he recognized several hundred feet of sandstones and shales, extending to the Benton, the upper part of which he says probably belongs to the Dakota formation. In the dark shales and sandstones which he refers to the Benton he obtained shells, all of Benton types. The Benton is succeeded above by grey sandstones and shales with some bands of limestone. He estimates these beds to have a thickness of 700 to 800 feet and refers them to the Niobrara, speaking also of the coal occurring above the middle. This coal and the beds below are probably to be correlated with the Eagle formation. In the upper part of the series not far below the top, I obtained a *Sequoia Reichenbachi*, probably the same species of Sequoia noted by Douglas as occurring near the same horizon in these beds. The beds so far as observed are nearly vertical in position, forming hog-back ridges, and the change to the badland beds, which are stratigraphically higher and nearly horizontal in position, occurs within a very short distance, though there is little doubt as to the two being conformable. These fresh-water beds are those which he calls the Fish Creek beds and he correctly correlates them with the Belly River beds of Canada with which their stratigraphic position agrees perfectly. They are overlain, as are the Canadian Belly River beds, by a great thickness of Fort Pierre shales. These exposures, first discovered by Douglas, are referred to by Stanton as follows:

> Not being familiar with the Judith River beds, Mr. Douglas was unable to recognize the identity of the Fish Creek and Judith River outcrops. In their stratigraphic position, as well as in their lithologic and faunal characters, they are almost identical with the Judith River beds farther north and should be referred to that formation.[2]

As noted above, the stratigraphic position of these beds is the same as that of the Belly River beds in Canada and not that of the Judith River beds of Montana. There is of course a general resemblance lithologically in them to the Judith River beds and

[1] *Economic Geology*, III (1908), 83, 84.

[2] *Bull. U.S. Geol. Surv. No. 257*, 1905, p. 59.

also to those of the Lance formation. It was this resemblance, as we have seen, that in Canada caused the confusion between the Belly River beds and the Edmonton beds in the minds of Dawson and other Canadian geologists. McConnell,[1] referring to some of the fresh-water and brackish-water shells that are common to the two, says:

> Their reappearance in the latter [Edmonton or Laramie] after a prolonged absence, during which the Pierre and Fox Hills—both marine formations—were deposited, affords an example of the extinction of a fauna over wide areas, its at least partial survival in sheltered localities, and the subsequent redistribution of some of its members over the same area on the recurrence of favorable conditions. . . . . Vertebrate remains occur in part of this formation, and are strewn in large quantities over the faces of some of the sections. They are, however, nearly always in a poor state of preservation, and crumble to pieces when disturbed.

This faunal resemblance is noted by all the Canadian geologists. Whiteaves,[2] referring to it, says that from purely invertebrate paleontological evidence the Belly River, Laramie [Lance] and Judith River beds cannot be separated from each other. As to the vertebrate fauna, Professor H. F. Osborn, who has made a comparison of the land and fresh-water forms from these various horizons, says that there is very little in common between the Belly River fauna and that of the Laramie [Lance] of Wyoming and Colorado so far as described, and that most of the dinosaurs will probably be found to be separated generically.[3] His table[4] shows that of the 35 species accredited to the Belly River series only 9 are common to the Judith River. As to the resemblance between the Judith River beds and the Lance formation more will be said later on. There are no Ceratopsidae in common and this we find to be the case with the Belly River series in the Fish Creek section and in the Willow Creek section which was the one next examined by us.

On Willow Creek the section begins with outcrops of Benton shales. Above these shales is a series of sandstones and shales

[1] *Geol. Surv. Canada*, Vol. I, 1885, Montreal (1886), p. 65*c*.

[2] *Contributions to Canadian Paleontology, U.S. Geol. Surv.*, I, 55.

[3] *Contributions to Canadian Paleontology*, III, Pt. 2 (1902), p. 10.

[4] *Ibid.*, pp. 11 f.

exactly like those near Crawford's ranch on Fish Creek, which, there the same as here, dip beneath badlands exposures of Belly River beds, having a total thickness of about 180 feet. The Belly River beds, here, closely resemble those seen in the Fish Creek section and, like them, pass conformably beneath the soft dark shales of the Pierre, all dipping gently toward the southeast. The Belly River beds contain fossil wood in abundance near the base of the outcrops, and a few feet higher in the section the plants were collected which were described by Dr. Knowlton[1] and said to exhibit an undoubted relationship with the flora of the Dakota group and very little affinity with that of the Laramie or Fort Union as they would if from the true Judith River beds. There can be no doubt as to the Belly River age of these beds. They contain the usual fresh-water shells and the overlying beds contain a characteristic Pierre fauna referred by Dr. Stanton to the Bearpaw. The beds between the top of these Fort Pierre shales and the Fort Union horizon, from which a typical Fort Union flora was obtained and which Dr. Stanton says[2] "should, from their stratigraphic position, contain the equivalent of the Fox Hills and the Laramie as well as the Livingston formation," are of Lower Fort Union age—that is, are referable to the Lance formation. These (Lance) beds rest immediately upon the Pierre without any Fox Hills or Livingston beds between them, and as for the Laramie, no beds referable to this formation have yet been found in this region. A careful search was made for Fox Hills fossils, but not a trace could be found of them nor of anything referable to the Livingston, so, as at Forsyth, which was the last place visited by us, the Lance formation is in immediate superposition on the shales of the Fort Pierre.

[1] *Bull. U.S. Geol. Surv. No. 257*, 1905, pp. 129–55.

[2] *Ibid.*, p. 58.

MODIFICATIONS OF THE *QUANTITATIVE SYSTEM OF CLASSIFICATION OF IGNEOUS ROCKS*

WHITMAN CROSS, J. P. IDDINGS, L. V. PIRSSON, H. S. WASHINGTON

During the nine years that have elapsed since the publication of the *Quantitative System of Classification of Igneous Rocks* it has been used with increasing frequency by petrographers in all parts of the world. Naturally, it has been chiefly employed in conjunction with the qualitative system as a means of more exact definition, and as an aid in the correlation and comparison of rocks from different regions. Besides the commoner rocks that belong to the systematic divisions for which magmatic names were originally suggested, numerous varieties have been described that belong to divisions not named by the authors of the system, and some that were not known to exist at the time of its publication. For these divisions magmatic names have been suggested by petrographers from time to time, and the following have come to our attention since the first appearance of the system in 1902:

I. 2.2.3. Cardiffose (F. D. Adams and A. E. Barlow, 1910).

I. 3.1.4. Taurose (H. S. Washington, 1904).

I. 5.3. Piedmontase; I. 5.3.4. Piedmontose (T. L. Watson and S. Taber, 1912).

I. 5.3.2. Mazarunose (H. S. Washington, 1903).

I. 5.5.4–5. Caledonose (Lacroix, 1911).

I. 6.2.3. Procenose (H. S. Washington, 1906).

I. 6.2.5. Raglanose (F. D. Adams and A. E. Barlow, 1908).

I. 7.1.2. Craigmontose (F. D. Adams and A. E. Barlow, 1908).

I. 7.1.3. Appianose (H. S. Washington, 1906).

I. 8.2. Monmouthase; I. 8.2.4. Monmouthose (Adams and Barlow, 1908).

I.II. 1.5. Indare; I.II. 1.5.1. Uralase; I.II. 1.5.1.3. Uralose (H. S. Washington, 1903).

I.II. 1.5.3. Dungannonase; I.II. 1.5.3.4. Dungannonose (Adams and Barlow, 1908).

I.II. 1.5.4. Borsowase; I.II. 1.5.4.3. Borsowose (H. S. Washington, 1903).

I.II. 1.5.5. Kyschtymase (H. S. Washington, 1903).
II. 5.1.5. Kirunose (Geijer, 1910).
II. 5.3.2. Auruncose (H. S. Washington, 1906), Lincolnose (Ida Ogilvie, 1907).
II. 6.2.2. Vicose (H. S. Washington, 1906).
II. 7.1. Lujavrase (C.I.P.W., 1902). Chibinase, II. 7.1.4. Lujavrose (C.I.P.W., 1902). Chibinose (V. Hackman, 1905).
II. 7.2.2. Braccianose (H. S. Washington, 1903).
III. 4.4.4–5. Koghose (Lacroix, 1911).
III. 5.5.4–5. Ouenose (Lacroix, 1911).
III. 6.1.3. Montanose (L. V. Pirsson, 1905).
III. 6.3.2. Ottajanose (A. Lacroix, 1907).
III. 6.4.3. Papenoose (A. Lacroix, 1910).
III. 7.2.2. Jugose (H. S. Washington, 1906).
III. 7.2.3. Cascadose (L. V. Pirsson, 1905).
III. 7.3.2. Fiasconose (H. S. Washington, 1906).
III. 8.1.5. Tavose (V. Hackman, 1905).
IV. 1.2. Quebeciare; IV. 1.2.2. Brunase (J. A. Dresser, 1909).
IV. 1.2. Hawaiiare; IV. 1.2.1. Hilase; IV. 1.2.1.2. Hilose (Daly, 1911).
IV. 1.2.2.2. Palisadose (J. V. Lewis, 1907); Hudsonose (G. S. Rogers, 1911); Thiose (Lacroix, 1911).
IV. 2.1.2. Yamaskase; IV. 2.1.2.2. Yamaskose (G. A. Young, 1904).
IV. 2.3.3.2. Naketose (Lacroix, 1911).
IV. 3.[P].2.3. Tuxenose (E. Gourdon, 1908).
IV.II.3.1.2.3. Roselandose (Watson and Taber, 1912).
V. 1.3.2.2. Koswose (J. P. Iddings, 1903).
V. 1.4. Gorduniare; V. 1.4.1. Gordunase; V. 1.4.1.1. Gordunose (U. Grubenmann, 1908).
V. 1.4.1.2. Kakoulimose (A. Lacroix, 1911).
V. 1.5.1.2. Guineose (A. Lacroix, 1911).
V. 2.5.1.2. Permose (J. P. Iddings, 1903).
V. 3. Rhodare; V. 3.5.1. Rhodase; V. 3.5.1.2. Rhodose (C. H. Warren, 1908).
V.II. 2. Mainare; V.II.2.3. Mainiase; V.II.2.3.1.2. Lermondose (E. S. Bastin, 1908).
V.II. 5. Virginare; V.II.5.5. Virginore. (T. L. Watson and S. Taber).
V.II. 5.5.3. Nelsonase; V.II. 5.5.3.5. Nelsonose (T. L. Watson and S. Taber, 1912).
V.II. 5.5.4. Virginase; V.II. 5.5.4.5. Virginose (Watson and Taber, 1912).

There are a few synonyms in this list and in such cases we believe that the law of priority should be applied. Some names

are unnecessary, such as those for presodic subrangs of percalcic rangs, viz: Caledonose and Ouenose.

Recently O. C. Farrington has applied the quantitative system to the classification of stony meteorites, and has suggested 41 new names in conformity with this system, most of them in Classes IV and V, and in subclasses characterized by prominent amounts of metallic minerals. In several cases in which meteorites belong to magmatic divisions already named for rock magmas Professor Farrington has given new names for meteoric magmas in order to distinguish the two groups of bodies.[1]

MODIFICATION OF THE FORMATION OF RANGS AND SUBRANGS IN CLASSES IV AND V

Owing to the fact that the alkali-bearing femic molecules, $NaFe(SiO_3)_2$, Na_2SiO_3, and K_2SiO_3, are not present in rocks of Classes IV and V in sufficient amounts to necessitate the recognition of the femic alkalies in establishing rangs in these classes, although it is conceivable that rocks composed almost wholly of acmite may occur, it is advisable to shift the position of femic alkalies, $Na_2O''K_2O''$, in the arrangement of the base-forming components for the formation of rangs and subrangs. Comparison between them should be made as follows:

Rangs, according to the ratio $\frac{MgO+FeO+(Na_2O''+K_2O'')}{CaO''}$

Subrangs according to $\frac{MgO}{FeO+(Na_2O''+K_2O'')}$

Sections of subrangs, when needed, according to $\frac{FeO}{Na_2O''+K_2O''}$

Subsections of subrangs, when needed, according to $\frac{Na_2O''}{K_2O''}$

For all rocks so far known, sections and subsections of subrangs in these classes are not needed and may be neglected. When noticeably alkalic prefemic rocks are found, their place in the system is provided for. By this change the symbols for magma divisions in Classes IV and V are simplified in all cases so far known, by the

[1] Farrington, O. C., Field Museum of Natural History, Chicago, *Pub. 151*, Geol. Ser., Vol. III, No. 9, 1911.

omission of sections of rangs. Those divisions previously called sections of rangs will become rangs with the appropriate change in the suffix. That is, the name hitherto used for the section of rang is to be retained as the name of the rang of the corresponding number, 1, 2, 3, etc., and *i* dropped from the suffix. Thus in Class IV, Order 2, Section 2 (paoliare), Rang 1 will be valbonase, and Rang 3, paolase. In Section 3, texiare, of the same order, Rang 1 will be marquettase; Rang 2 uvaldase. The name texase will be dropped unless subsequently applied to either Rang 3, 4, or 5 of this Section 3. The subrangs remain as first described and named.

Since in Classes II and III subgrads are formed on a basis of the chemical characters of the femic minerals, the process of determining them is to be modified in accordance with the method just described for determining rangs in Classes IV and V. That is, subgrads are to be determined by the ratio $\frac{MgO+FeO+(Na_2O''+K_2O'')}{CaO''}$; sections of subgrads, by the ratio of $\frac{MgO}{FeO+(Na_2O''+K_2O'')}$; and in the exceptional cases in which there is a notable amount of femic alkalies, subsections of subgrads are to be determined by the ratio $\frac{FeO}{Na_2O''+K_2O''}$.

Notation of divisions and symbols.—In order to avoid confusion in the symbols for various divisions in the system, it has been found advisable to number threefold divisions, when used, in conformity with fivefold ones; thus, 1–2, 3, 4–5; since the first division comprises 1 and 2 of the fivefold; the second division corresponds exactly to 3 of the fivefold divisions; and the third division comprises 4 and 5 of the fivefold divisions. This method has already been employed in a number of publications[1] since the first appearance of the system in 1902. It is also advisable to print the numbers of subclasses, suborders, and sections so as to distinguish them from the numbers of regular divisions by placing them below the line rather than above it, thus:

[1] H. S. Washington, "The Superior Analyses," etc., U.S. Geological Survey, *Prof. Paper 28*, 1904; J. P. Iddings, *Igneous Rocks*, Vol. I, 1909, and others.

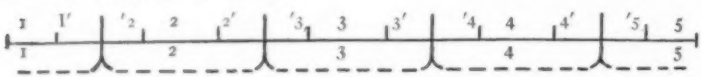
I.II. 5.2.3.=Class I, Subclass II, Order 5, Rang 2, Subrang 3.
IV.II. 2.3.2.2.=Class IV, Subclass II, Order 2, Section 3, Rang 2, Subrang 2.
IV. 4.2.1.4.=Class IV, Order 4, Suborder 2, Rang 1, Subrang 4.

It is to be observed, however, that the number for subrang is placed on the line with rang. This arrangement makes it possible to express the intermediate magmatic divisions by means of marks above the line in the manner explained in the next paragraph.

Intermediate divisions.—In a continuous series of varieties of rock magmas those near one another on opposite sides of any division line are more alike than varieties at the extremities of any one division. And so it happens that some rocks differing but little in composition may be given different names, because they belong on two sides of a division line, while other rocks not so much alike are called by the same name and belong to the extremes of the same magmatic division. This condition is inherent in any rigid system of divisions of continuous series. It has not been felt to the same extent in the qualitative system because each petrographer adjusts the elastic definitions of that system to suit his own requirements, and to the confusion of everyone else.

In order to distinguish the extremes of the magmatic divisions already established in the first publication of the *Quantitative System*, and meet the needs of closer classification, or correlation, it is desirable to establish *intermediate divisions* throughout the system by placing the boundaries of these divisions half-way between the extremities of the divisions and the centers of the divisions from which the intermediate divisions are to be taken, in conformity with the methods pursued in establishing the first division in the *Quantitative System*. The boundary between adjacent divisions becomes in this way a new centerpoint for each pair of intermediate divisions.

In the notation of intermediate divisions the halves of each pair of divisions falling within the adjacent large divisions are designated as parts of the large divisions, and are not given new and independent designations. Thus the intermediate divisions in any fivefold series are as follows:



In order to simplify the expression of these divisions they are printed with prime marks as follows: 1, 1′, ′2, 2, 2′, ′3, 3, 3′, etc. A rock may belong to I, 2′, ′4, 3, or I′, 2, ′2, 3′. For convenience in determining the position of any magma with respect to these divisions a scale of ratios is given in Fig. 1. Magmas belonging to intermediate divisions may be described in terms of the variations indicated by the symbols; as, for example, I′, 3, 2′, 3 (tehamose) is a femic, calcic tehamose; more precisely, a more femic, more calcic tehamose than the central varieties, since these also contain femic and calcic components.

Transitional magma names.—It was pointed out in the first publication of the *Quantitative System*, p. 166, that a rock whose magma belongs so near a boundary line between named divisions that it should be considered a transitional variety should receive a compound magma name, made by uniting the names of the two divisions concerned and connecting them with a hyphen. The name of the division within which the magma belongs is placed last. This has been done in numerous instances, but no definite statement has been made as to the limits of the magmas that may be called transitional. It is here proposed to fix the limits half-way between the boundary between named or numbered divisions, and the boundaries of the intermediate divisions described in the preceding paragraphs. This conforms to the general principles of divisions in the *Quantitative System* and establishes a still smaller division of the petrographic series. It does not appear desirable to extend the use of compounded names to the whole range of intermediate magmas, which are sufficiently designated by symbol.

In case a rock is transitional in more than one respect, as in subrang and in rang, or in rang and order, or in class, order, and rang, or in all possible respects, it is necessary for convenience to select two magmatic names to form the compound name, and express the remaining transitions by descriptive terms or symbols. Since the magmatic name commonly employed in designating a rock is that of its subrang, the name to be compounded with it should be that of the subrang toward which it is transitional through the nearest classificatory division in which it is transitional. Thus, in the case of a rock whose symbol is II.$(3)_4 \cdot 3(4) \cdot 4$; that is, one

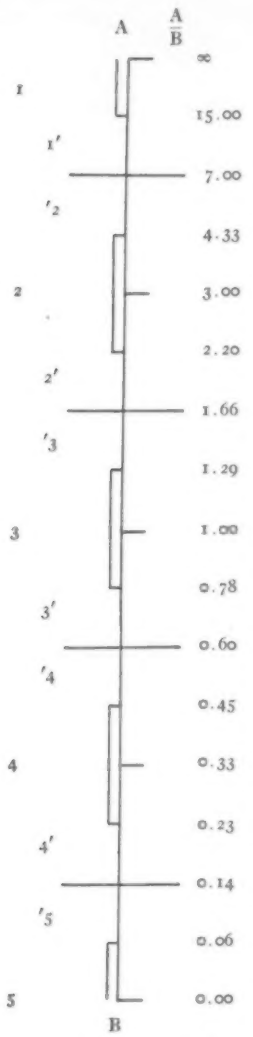


FIG. 1.—Limiting Ratios for Intermediate Magmas.

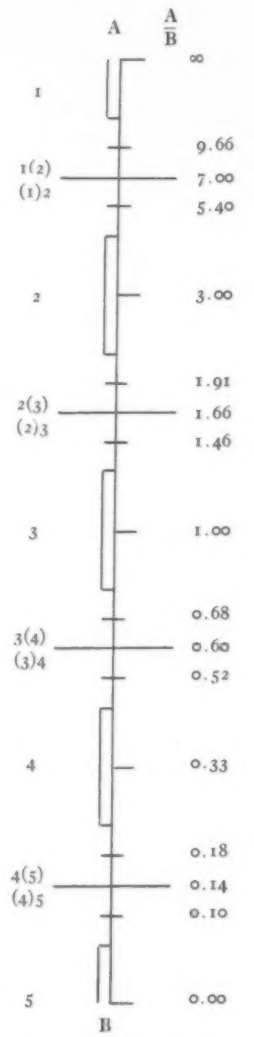


FIG. 2.—Limiting Ratios for Transitional Magmas.

which is in Order 4, near 3, and in Rang 3, near 4; the name for the subrang is tonalose, but as it is near Rang 4 it should be called bandose-tonalose; and the transition toward Order 3 should be expressed by describing it as extremely quaric bandose-tonalose. If it were transitional toward Class I, it would be extremely salic; if toward Class III, extremely femic—the term *extremely* signifying that it is *near the limit* of the division with respect to the factor named, the actual amount being small in some cases. A scale of ratios to be used in determining the limits of transitional divisions is shown in Fig. 2.

In order to express in the symbol that a rock has a *transitional* position in the quantitative classification, the number of the division toward which it is transitional is to be placed in curves, thus I.4(5).2.(3)3, or II.5.'3.4(5).

Experience has already shown that it is eminently undesirable to base subrang or other names on occurrences of *transitional* rocks.

Changes in the norm.—It has been found advisable to omit the calculation of normative sodalite and noselite on a basis of the Cl and SO_3 in rock analyses, because these substances are such small components of sodalite and noselite molecules that any error in the assignment of Cl or SO_3 to these molecules may make a large error in the amount or normative noselite and sodalite. Moreover, there are difficulties in the analytical determination of Cl and SO_3 on the one hand, and they may occur in quite different mineral compounds on the other. The method of calculating the norm has been modified, therefore, by allotting to Cl and SO_3 sufficient Na_2O to form NaCl and Na_2SO_4, and including these compounds among the salic components. This modification has been incorporated in the statement of the *Quantitative System* in Vol. I of *Igneous Rocks* by one of the authors.

The rule with regard to the allotment of CaO and TiO_2 to form titanite or perovskite is to be modified to suit those cases in which there is no excess of CaO after calculating anorthite; that is, when there is no femic CaO. In the ordinary case in which titanite, or perovskite, is formed there is femic CaO available, but there are magmas, not commonly met with, in which anorthite is associated with abundant rutile, as in certain rutile-bearing pegmatites.

From these it is seen that aluminum and calcium combine to form the orthosilicate, anorthite, in the presence of uncombined TiO_2, so that the rule regarding the calculation of titanite and perovskite, rule 3(*b*), should be modified to read: Excess of TiO_2 over available FeO is combined with CaO in the ratio of CaO: TiO_2::1:1 for titanite and perovskite, *after the allotment of CaO to Al_2O_3 for anorthite*, rule 5(*a*), and according to the silica available, etc.

Recent investigations in the Geophysical Laboratory of the Carnegie Institution in Washington have shown that the akermanite compound is $3CaO.2SiO_2$, not $4CaO.3SiO_2$ as formerly stated. This involves changes in the formulae for the calculation of normative akermanite as follows:

For the reduction of diopside to akermanite

$$V = \tfrac{2}{5} \text{ of the deficit of } SiO_2$$
$$V = \text{molecules of akermanite } (3CaO.2SiO_2).$$

For the reduction of wollastonite to akermanite

$$V = \text{deficit of } SiO_2$$
$$V = \text{molecules of akermanite } (3CaO.2SiO_2)$$

If there is not sufficient wollastonite to satisfy the deficit of silica, recalculate the molecules of diopside and wollastonite so as to make akermanite, olivine, and diopside by means of the formulae

$$2x+2y+\frac{z}{2} = \text{available } SiO_2$$
$$x+3y = \text{molecules of CaO}$$
$$x+z = \text{molecules of MgO+FeO}$$

Where x=molecules of new diopside, y=molecules of akermanite, and z=molecules of olivine.

Common errors in the calculation of norms.—Although clearly explained in the statements published regarding the method of calculating normative minerals in the *Quantitative System* and the method of determining rangs and subrangs, there often appears to be a misunderstanding in the minds of some petrographers as to the CaO and K_2O and Na_2O, which are to be used in determining the rang of a rock in Classes I, II, and III. It is a common error to use all the CaO and K_2O+Na_2O in the rock analysis in the ratio

$\frac{CaO'}{K_2O'+Na_2O'}$, instead of only the salic CaO and salic K_2O and Na_2O; that is, only the CaO allotted to normative anorthite, and only the K_2O and Na_2O allotted to normative orthoclase, albite, leucite, nephelite, and NaCl or Na_2SO_4. In like manner the CaO, Na_2O, and K_2O used in determining rangs, subrangs, and sections of subrangs in Classes IV and V by the ratios $\frac{MgO+FeO+Na_2O''+K_2O''}{CaO''}$, etc., are only the femic CaO and femic Na_2O and K_2O; that is, the CaO that has not been allotted to anorthite, and the Na_2O and K_2O not allotted to salic minerals.

An error is sometimes made in calculating the rangs and subrangs in classes IV and V. The MgO and FeO involved are all the MgO and FeO in all the femic minerals, silicates and non-silicates; that is, all in the rock analysis.

Misuse of the terms salic and femic.—There appears to be an indifference among petrographers as to the correct use of scientific terms, which is perhaps inherent in the conditions attending the beginnings of any new branch of science, and suggests that indifference to the manners and customs of old established communities which is characteristic of frontier life in newly settled countries. It indicates a sense of self-sufficiency on the part of the individual petrographer which, in the matter of his use of words, is typified in the conscious superiority of "Alice's" friend "Humpty Dumpty" over these servants of human speech.[1] The petrographer also has no intention of being mastered by mere words, and is in the habit of using them as he himself chooses, without regard to original

[1] "There's glory for you," said Humpty Dumpty.

"I don't know what you mean by glory," Alice said.

Humpty Dumpty smiled contemptuously. "Of course you don't—till I tell you. I meant there's a nice knock-down argument for you!"

"But glory doesn't mean 'a nice knock-down argument,'" Alice objected.

"When *I* use a word," Humpty Dumpty said in rather a scornful tone, "it means just what I choose it to mean—neither more nor less."

"The question is," said Alice, "whether you *can* make a word mean so many different things."

"The question is," said Humpty Dumpty, "which is to be master—that's all."—*Through the Looking Glass*, by Lewis Carroll; Carl Ludwidge Dodgson, Mathematician, Oxford.

definition, or others' usage. Witness the frequent misuse of the chemical terms "acid" and "basic" as applied to the limesoda-feldspar series. Oligoclase is often said to be a more "acid" feldspar than andesine, and labradorite a more "basic" one. It is not to be assumed that petrographers misusing these terms are wholly ignorant of chemistry. We, also, are petrographers and understand how we have done such things. We plead guilty to various degrees of indifference, lack of enterprise, and ignorance.

The petrographical custom of redefining any rock name to suit individual preference and the resulting multiplicity of definitions is, no doubt, in part responsible for this common indifference to all technical terms, whether distinctively petrographic or derived from other sciences. In some cases, names of rocks and technical terms have been so vaguely defined in the first instance that there is latitude of judgment in their application and an invitation to improve their definition. But when the first definition of any term has been precise and clearly specific, its misuse and distortion are inexcusable.

The terms *salic* and *femic* were applied definitely to certain minerals chosen to form norms of igneous rocks in the *Quantitative System of Classification*. They were applied strictly to calculated normative minerals: *salic* to normative quartz, feldspar, lenads, zircon, and corundum; *femic* to normative non-aluminous ferromagnesian, and calcic pyroxenes, olivines, and other minerals specifically enumerated and described. It excluded aluminous pyroxenes, amphiboles, micas, etc., to which the term *alferric* was applied.

Some petrographers have fancied the terms salic and femic as short words, which they wish to apply to modal quartz, feldspar, and feldspathoid minerals in one case, and to all modal ferromagnesian minerals in the other. These terms have also been applied to major rock groups. Such applications are not proper uses of these terms, and introduce confusion where it can be easily avoided.

Felsic and mafic.—Short expressions are useful in the general or qualitative description of rocks for the feldspathic minerals and quartz on the one hand, and for the ferromagnesian minerals on the

other. The proper course is to create new terms for new or distinct conceptions, and not use one technical word in two or more quite different ways. To do so is as though some one should call all mammals *marsupials*, because he prefers the word marsupial; or should call all predaceous birds owls, because it is a short, convenient word. Since short, comprehensive terms are needed for modal feldspathic minerals, and for modal ferromagnesian minerals, and for rocks made up predominantly of these groups of minerals, we suggest the term *felsic* for the group of modal feldspars, feldspathoids, and quartz, and the term *mafic* for the group of modal ferromagnesian minerals of all kinds. The term *femag* has been used recently by Johannsen[1] for ferromagnesian minerals, but it appears to us to be objectionable both in form and in sound.

[1] A. Johannsen. *Jour. Geol.*, XIX (1911), 319.

ISOSTASY, A REJOINDER TO THE ARTICLE BY HARMON LEWIS

JOHN F. HAYFORD
Director, College of Engineering, Northwestern University

In the *Journal of Geology*, Vol. XIX, No. 7, October-November, 1911, pp. 603–26, there was published an article by Mr. Harmon Lewis, entitled "The Theory of Isostasy," which is a direct attack on three publications by John F. Hayford, namely, *The Figure of the Earth and Isostasy from Measurements in the United States, Supplementary Investigation in 1909 of the Figure of the Earth and Isostasy*, both published by the Coast and Geodetic Survey, and "The Relations of Isostasy to Geodesy, Geophysics and Geology" published in *Science*, pp. 199–208, February 10, 1911. The attack is direct and positive. Hence this rejoinder is written in a similar manner. The critic may not reasonably object to having his article treated in the manner in which he has treated the publications criticized.

Mr. Lewis claims in his article that Hayford has made a fundamental error in his geodetic investigation, an error in method which vitiates all the conclusions reached. The greater portion of the article is devoted to setting forth this alleged error of method and its consequences. A few pages in the article are devoted to the proposition that since the theory of isostasy does not explain all of the geological facts which have been observed, isostasy probably does not exist.

Hayford believes that Mr. Lewis has in his article, probably unintentionally, overstated even his own extreme views. Hayford is certain that the alleged fundamental error in method in the geodetic investigation, which Lewis sets forth, is not an error and, moreover, that if Lewis had followed his own line of thought to its logical conclusion, he would have convinced himself that no error had been made. The forms of statement used by Mr. Lewis lead one to think that he has some positive basis for other

conclusions from the geodetic evidence than those given by Hayford. A careful reading of the article shows, however, that Lewis has simply suggested that other conclusions are possible. Hayford believes that the arguments in Mr. Lewis' article which are based on geological evidence are essentially weak and in part erroneous.

This rejoinder is an attempt to show briefly some of the basis for the writer's beliefs as expressed in the preceding paragraph. In the first part of this rejoinder practically all of the evidence cited was available to Mr. Lewis before he wrote his paper. In the latter part some new evidence, from gravity observations, is utilized which has not heretofore been accessible to Mr. Lewis but which is now accessible to all interested persons.

Mr. Lewis claims that Hayford made a fundamental error in that "the most probable depth was calculated on the assumption of completeness. If the assumption of completeness was wrong, the depth of compensation which would appear most probable would not be the true depth of compensation but a depth which would counteract the effect of the wrong assumption in regard to the completeness" (p. 612). Referring to the same matter, on p. 625, Mr. Lewis writes, "It is believed that Hayford made an error in determining the degree of completeness of compensation which invalidates his conclusions, for he assumed complete compensation in calculating the depth and then used this depth to calculate the degree of completeness." In contrast to the published conclusions by Hayford,[1] Mr. Lewis writes in connection with the same matter (p. 612), "We are forced to conclude that, from the geodetic evidence alone, neither the depth nor the degree of completeness of isostatic compensation can as yet be considered settled."

Recur for a moment to Mr. Lewis' statement (p. 612), that "If the assumption of completeness was wrong, the depth of compensation which would appear most probable would not be the true depth of compensation but a depth which would counteract the effect of the wrong assumption in regard to completeness." This statement involves in itself an assumption which is absolutely essential to Mr. Lewis' whole argument, namely, that the counter-

[1] See *The Figure of the Earth and Isostasy*, pp. 164–66, 175, and *Supplementary Investigation*, pp. 59, 77.

action suggested by him is possible. Now it happens that such counteraction is nearly impossible to any appreciable extent in the computations actually made. If Mr. Lewis had followed his own course of reasoning farther than he did, using the data printed in the publications criticized he would have convinced himself of this.

He carries his reasoning farther on pp. 616–17 than elsewhere in his article. In the paragraph commencing near the top of p. 616 he shows that if with assumed complete compensation the assumed depth of compensation is made smaller, the reduction factors for each ring become smaller and that, on the other hand, if the isostatic compensation is assumed to be less than complete, the reduction factor for each ring becomes larger. It is also shown that when both these changes in assumption are made at the same time, the reduction factor becomes smaller for certain rings and larger for others. On p. 617 a concrete case of this kind is shown. The table there printed shows clearly that if in the place of assumed complete compensation extending to depth 113.7 km. one assumes a compensation but one-half complete and extending only to the small depth 19.29 km., the reduction factors for rings 29 to 13, corresponding to topography within 56 km. of the station, are all made smaller and those for the remaining more distant rings are all made larger. Thus far Mr. Lewis' reasoning and results are all correct. For convenience, call such reduction factors as those shown in the middle column of the table on p. 617, Lewis factors, and call those such as are shown in the last column, Hayford factors.

At this point Mr. Lewis' logical process begins to go wrong. For at this point the tacit assumption is made, though not stated, that if the Lewis factors are smaller for some rings and larger for others than the Hayford factors the computed topographic deflections with the isostatic compensation considered will be about the same in the two cases. If so (that is, if the computed deflections are easily made about the same), then with effort corresponding to that already made by Hayford, other factors on Lewis' basis, involving other assumptions as to depth and degree of compensation, can be found which will produce computed deflections more nearly in agreement with the observed deflections

than are those computed by Hayford. This is essentially Mr. Lewis' reasoning.

The tacit assumption is, however, not even approximately true, as shown in the following paragraphs, and hence all reasoning based on the assumption leads to erroneous conclusions.

The reduction factor under discussion is the factor by which topographic deflections for a given ring must be multiplied to secure the resultant deflection due to both the topography and the assumed compensating deficiency or excess of mass below the surface of the earth.

On pp. 26–33 of *The Figure of the Earth and Isostasy* five complete examples of the computations of the topographic deflections are printed. Note that this is one of the publications criticized by Mr. Lewis. His tacit assumption has been tested by using these examples, just as he himself should have tested it.

In the following table the details of the test are shown for two stations. The value shown in the table for each ring is the resultant deflection due both to topography and to the assumed isostatic compensation. The values in the first column which is under the heading "Point Arena" correspond, as indicated in the heading, to the assumption that isostatic compensation is but one-half complete and that it extends to the depth 19.29 km. Each value was obtained by multiplying the topographic deflection for the particular ring, as shown in the example on p. 32 of *The Figure of the Earth and Isostasy*, by the Lewis factor shown on p. 617 of his article. The next column shows the deflections for each ring corresponding to the assumption that the isostatic compensation is nine-tenths complete and the depth as before 19.29 km. The Lewis factors necessary for use in computing this column, as well as those mentioned elsewhere in this rejoinder, were computed from the formula given on p. 615 of the Lewis article. The third column shows the deflections corresponding to the assumption that the compensation is complete and the depth 113.7 km.

According to Mr. Lewis' reasoning the total for the first column under Point Arena, +53″.73, should differ but little from the total for the third column, +15″.67. The actual difference, 38″.06, is very large. Similarly the corresponding difference for Uncom-

pahgre, namely, between $-3''.93$ and $+5''.55$ is also large, $9''.48$. Evidently the factors given as examples by Mr. Lewis on p. 617 did not produce the results expected by him.

Ring	Longitude Station No 1 Point Arena, Cal.			Latitude Station No. 54 Uncompahgre, Colo.		
	Lewis $M=.5$ $h_1=19.29$	Lewis $M=.9$ $h_1=19.29$	Hayford $M=1.0$ $h_1=113.7$	Lewis $M=.5$ $h_1=19.29$	Lewis $M=.9$ $h_1=19.29$	Hayford $M=1.0$ $h_1=113.7$
30	+ ″.02	+ ″.02	+ ″.02	—	—	—
29	+ .04	+ .04	+ .04	—	—	—
28	+ .04	+ .04	+ .04	—	—	—
27	+ .05	+ .05	+ .05	—	—	—
26	+ .02	+ .02	+ .02	+ ″.27	+ ″.26	+ ″.27
25	+ .02	+ .02	+ .02	+ .28	+ .28	+ .29
24	+ .01	+ .01	+ .01	+ .21	+ .21	+ .22
23	+ .10	+ .09	+ .10	+ .14	+ .14	+ .15
22	+ .12	+ .12	+ .13	− .07	− .06	− .07
21	+ .15	+ .14	+ .16	+ .03	+ .03	+ .03
20	+ .14	+ .13	+ .15	+ .05	+ .05	+ .06
19	+ .22	+ .19	+ .25	− .33	− .28	− .36
18	+ .25	+ .20	+ .29	− .36	− .29	− .41
17	+ .28	+ .21	+ .34	+ .22	+ .16	+ .26
16	+ .43	+ .27	+ .55	+ .67	+ .42	+ .85
15	+ .90	+ .45	+1.17	+ .92	+ .46	+1.19
14	+1.34	+ .53	+1.69	+1.05	+ .42	+1.33
13	+2.11	+ .66	+2.42	+1.27	+ .40	+1.45
12	+2.59	+ .68	+2.46	+ .75	+ .20	+ .71
11	+3.01	+ .70	+2.11	+ .07	+ .01	+ .04
10	+2.90	+ .63	+1.34	− .50	− .11	− .23
9	+3.01	+ .62	+ .83	− .54	− .11	− .15
8	+4.59	+ .95	+ .71	− .02	.00	.00
7	+4.72	+ .95	+ .38	− .42	− .08	− .03
6	+5.05	+1.02	+ .20	− .30	− .06	− .01
5	+4.66	+ .93	+ .09	− .58	− .12	− .01
4	+5.04	+1.01	+ .05	− .82	− .16	− .01
3	+5.02	+1.00	+ .03	−1.34	− .27	− .01
2	+4.09	+ .82	+ .01	−2.04	− .41	.00
1	+2.81	+ .56	+ .01	−2.54	− .51	− .01
Totals	+53.73	+13.06	+15.67*	−3.93	+ .58	+5.55*

*The slight discrepancies, too small to be of any consequence, between these totals and those printed on p. 55 of *The Figure of the Earth and Isostasy* are due to the effects of omitted decimal places.

Possibly it might be said by Mr. Lewis that this failure to secure a close agreement is due to having made so great a reduction in the assumed completeness of compensation as to much more than counteract the reduction in the assumed depth of compensation. Accordingly the middle column has been inserted in the above

table corresponding to the assumption that the compensation is nine-tenths complete and the depth is 19.29 km. This gives a closer agreement in each case, as should be expected, since the assumption is nearer to that made by Hayford, but still the differences from Hayford's values are large—2".61 for Point Arena and 4".97 for Uncompahgre.

If Mr. Lewis had followed out his own line of thought, when he reached this point he should have inquired what value of M, expressing in his notation the completeness of compensation, would make his values agree with Hayford's values. If he had done so he would have found that a close agreement would occur for Point Arena with M assumed to be about .87 and thus the truth of his tacit assumption would apparently have been confirmed.

Again, if he had tried Mt. Ouray he would have found that with $M = .2$ and $h_1 = 19.29$ km. the total computed deflection is $-10".02$, practically in agreement with the Hayford value. Note the contrast between the reduction to compensation only one-fifth complete necessary at this station to neutralize the effect of the assumed reduction in depth of compensation and the comparatively slight reduction, to .87, necessary at Point Arena.

But if Mr. Lewis had continued still farther and tried the same thing for Uncompahgre he would have found that for $M = 1.34$ and $h_1 = 19.29$ km. the total computed deflection is $+5".47$, practically in agreement with Hayford's value. The value 1.34 for M indicates 34 per cent of over-compensation. In other words, for Uncompahgre it takes an assumption of one-third over-compensation to neutralize the assumption of a reduction of depth of compensation, whereas Mr. Lewis' whole argument is based upon the assumption that under-compensation is always necessary for such neutralization.

The following table shows the results of the tests made in preparing this rejoinder using the five stations[1] which were available to Mr. Lewis. Each of the Lewis values which lies nearest to the Hayford value for that station is printed in italics. The values

[1] For all the 733 stations involved in the investigation the total topographic deflections are printed, but those for each separate ring are printed for these five stations only. Hence these are the only stations on which it was possible for Mr. Lewis, using publications only, to make the test indicated.

in the table are the computed deflections on the different assumptions indicated. They correspond to the totals at the foot of the preceding table.

	Longitude Sta. No. 1, Point Arena, Cal.	Azimuth Sta. No. 59, Mt. Ouray, Colo.	Latitude Sta. No. 54, Uncompahgre, Colo.	Latitude Sta. No. 164 Calais, Me.	Azimuth Sta. No. 115, Knott Island, Va.
Hayford					
$M=1.0$, $h_1=113.7$	+15″.67	−10″.03	+5″.55	−0″.51	− 1″.90
Lewis					
$M=0.2$, $h_1=19.29$ ...	.....	−10.02	.....	.....	.....
$M=0.5$ $h_1=19.29$ ...	+53.73	− 8.22	−3.93	−16.00	−27.19
$M=0.9$ $h_1=19.29$ ...	+13.06	− 5.86	+0.58	− 2.97	− 5.52
$M=1.34$ $h_1=19.29$ ...	.....	.....	+5.47	.....	.....
$M=1.4$ $h_1=19.29$ ...	.....	.....	+6.19	.....	.....
$M=1.6$ $h_1=19.29$ ...	.....	.....	+8.36	.....	.....

If Mr. Lewis had constructed this table, which would have required less than a day of computation, he would have avoided the gross error into which he has fallen. Instead of believing, as indicated in his article, that a large reduction in assumed completeness of compensation of about the same amount for every station would neutralize the large change of assumed depth from 113.7 to 19.29 km. he would have known that for some stations such a neutralization requires a very large reduction of assumed completeness (to $M=.2$ at Mt. Ouray, for example), for others requires a very small reduction (at Point Arena, Calais, and Knott Island, for example), and for others requires an increase of assumed completeness, that is, over-compensation (at Uncompahgre, for example). He would have noticed that for these five stations the average value of M necessary to secure an agreement with the Hayford values is about .9, not far from unity.

If beginning to be skeptical of his own proposition that a reduction in completeness of compensation at all stations would counteract a reduction in assumed depth of compensation, and beginning to suspect that such a counteraction is impossible in the computations as actually made, he had then proceeded to examine into the matter more carefully he might have noted also the following things:

1. That the factors as printed on p. 617 differ very largely for separate rings from the Hayford factors. The maximum

difference is .499, whereas the factor itself can have a total range of only 1.000.

2. That for other various assumed values of M, with the same value of h_1, his factors always differ largely from Hayford's for some rings. If $M = .9$, for example, the maximum difference occurs on ring 14 and is .496.

3. That to secure a close agreement in the computed deflections from two sets of reduction factors used at various stations there must be a close agreement of the factors for the separate rings, not simply an agreement in the average values of the two sets of factors, since the computed deflections for the various rings at a given station differ greatly.[1] At Point Arena, for example, the topographic deflections for various rings vary from $+''.01$ for ring 24 to $10''.10$ for ring 6, and at Uncompahgre from $+2''.35$ for ring 13 to $-5''.07$ for ring 1. These topographic deflections for separate rings are the quantities which are multiplied by the reduction factors to obtain the computed deflections. Evidently at Uncompahgre a decrease in the reduction factor in ring 13 will not be partly neutralized in effect by an increase of the factor for ring 1, but instead the two effects will be of the same algebraic sign, since the topographic deflections for these rings happen to be of opposite signs.

4. That the proposed Lewis factors corresponding to incomplete compensation are always greater than the Hayford factors for the extreme outer rings (distant topography), and less than the Hayford factors in the inner rings corresponding to topography at a moderate distance. This gives a clue to the reason for the fact that at some stations it requires a decrease in assumed completeness and at other stations an increase to counteract an assumed decrease in depth of compensation. In this connection it is important to note that the 733 stations used in the computation being criticized are in a great variety of locations with reference to near and distant topography.

5. That following the clue suggested in (4), it becomes evident that there is no fixed relation between the effect upon the compu-

[1] Consult pp. 26–33 of *The Figure of the Earth and Isostasy*.

tations of a reduction in an assumed completeness and a reduction in depth.

6. That in a computation such as that being criticized, based upon 733 stations all utilized fully in a single computation, though an error of moderate size in assumed completeness of compensation will produce residuals at the separate stations, it will have an exceedingly small, probably inappreciable, effect on the computed depth of compensation.

7. That the residuals from the computation actually made, which residuals are printed in detail, show that the assumptions are in very close agreement with the truth, and especially that it is impossible that there is any large error in the assumed completeness of compensation.

8. Finally by following the clues indicated in (4) it would be noted that if it were a fact that the actual depth of compensation is much less than 113.7 km. and the compensation much less than complete the residuals of the accepted final computation would show a certain systematic geographic distribution. For example, all longitude stations and all azimuth stations situated on or very near the Pacific coast, like Point Arena, should have residuals of the same sign as Point Arena. The geographic distribution of residuals which would be so produced does not exist.[1]

In short, if Mr. Lewis had carefully examined the evidence available to him, following logically the lines of thought on which he started, he would have reached the conclusion that an error of moderate size in assumed completeness of compensation would produce no appreciable error in the depth of compensation as actually computed, and that the actual compensation certainly departs but little from completeness.

It should be clear from what is here printed that the alleged error in Hayford's method of computation on which Mr. Lewis' whole criticism rests is fictitious. Even if it is not clear to one who reads this very brief statement, it will certainly become perfectly clear to those who will examine the methods in detail with the numerical values before them.

[1] Consult illustrations 5 and 6 of the *Supplementary Investigation of the Figure of the Earth and Isostasy.*

Mr. Lewis suggests more than once in his article that possibly the existing condition is "an over-compensation at a greater depth for land areas with probably complete compensation for ocean areas" or "under-compensation at a shallower depth for land areas with complete or over-compensation for ocean areas" (p. 626).

If Mr. Lewis or anyone else will carefully test these ideas in the manner indicated on pp. 563–70 of this rejoinder he will certainly reach the conclusion that there is nothing in the suggestion. The writer had made such tests, and others, before Mr. Lewis' article was written.

To test such suggestions by complete computations, such as those set forth in Hayford's publications which are under criticism, would be a waste of time. It is not worth while to spend months in testing a suggestion by a complete computation if, as in this case, a rough test made in one or two days will show the suggestion to be in error.

Turn now to another direct and positive statement made by Mr. Lewis, which is closely allied with the questions discussed above. After stating, correctly, that all Hayford's principal computations were made on the assumption that the isostatic compensation is complete, Mr. Lewis continues thus (pp. 610–11), "This was a purely arbitrary assumption on Hayford's part since he gave no reason whatever for believing at the outset that compensation is complete, and furthermore the fact that he later attempts to find the degree of completeness implies that there is no reason to believe at the outset in complete compensation."

Hayford has indicated in various places in his publications that gravitation tends to produce a readjustment of the material composing the outer portion of the earth toward the condition of approximate equilibrium known as isostasy.[1]

Gravitation acts continuously. It certainly tends to produce complete compensation. Is it purely arbitrary to assume complete compensation as a first approximation? The writer believes it is not.

[1] Consult especially *The Figure of the Earth and Isostasy*, pp. 66–67, 166–68, and the Minneapolis address referred to in the first paragraph of this rejoinder. In this address the possible mechanics of the readjustment is indicated.

Moreover, it requires but little consideration to realize that the known shiftings of load at the surface tends to bring about over-compensation in some localities and under-compensation in others. For example, long continued erosion from a high mountainous region tends to produce over-compensation and deposition by a river of transported material at points above sea-level, as for example, during the raising of the land surface of a delta, tends to produce under-compensation. Various actions below the surface of the earth known to geologists and others tend to produce over-compensation in some locations and under-compensation in others. Gravitation by its continuous action tends, therefore, to cause the condition to approach complete compensation from the side of over-compensation in some localities and from the side of under-compensation in others. Gravitation is resisted by rigidity and it is, therefore, to be expected that it will be but partially successful in the attempt to produce complete compensation. The writer believes, therefore, that it was logical to assume that the compensation is complete rather than that either under-compensation or over-compensation predominates. The assumption was made, not arbitrarily, but logically.

However, it is clear that as long as the material composing the earth has some rigidity, some strength available to resist gravitation, and as long as other forces than gravitation certainly are in operation, complete compensation cannot be continuously produced and maintained by gravitation and one must expect local deviations, now of one sign now of the other, from complete compensation. Hence it was desirable to study the residuals from the computations made on the basis of complete compensation to ascertain if possible how much and in what direction the actual compensation departs from completeness in each locality. This has been done with considerable energy. From the investigations of the deflections the conclusion reached is that there is certainly under-compensation in some localities and over-compensation in others but that on an average the compensation departs less than one-tenth from completeness or perfection.[1] A similar conclusion

[1] *The Figure of the Earth and Isostasy*, pp. 164–66, 175, and *Supplementary Investigation*, p. 59.

is reached from the gravity investigation except that the departure of compensation from completeness is somewhat greater than one-tenth.[1]

Turning now to Mr. Lewis' article the present writer is quite willing to let the reader decide whether or not Mr. Lewis' assumptions (p. 626) of over-compensation for all land areas, or of under-compensation for all land areas and over-compensation for all ocean areas, are arbitrary.

The preceding parts of this rejoinder have dealt with those portions of Mr. Lewis' article, which are a discussion of the geodetic evidence of isostasy. Turn now to the portions of his article in which certain geologic evidence is interpreted as being adverse to the existence of isostasy.

On pp. 621–22 Mr. Lewis sets forth the argument that there is much geological evidence of horizontal movements in the outside portions of the earth especially in the form of folding, that the controlling movements of isostasy are assumed to be vertical and hence cannot account for folding, and that the horizontal movement or undertow concerned in isostatic readjustment must be below the depth of compensation and hence so far below the surface as to be very ineffective in producing folding.

There are two fatal defects in this argument as applied to controverting anything that Hayford believes or has written.

First, Hayford has already indicated clearly his belief that the undertow concerned in isostatic readjustment is above, not below, the depth of compensation. In both the figures published in his Minneapolis address the undertow is clearly indicated as being above the depth of compensation and it is also so indicated in the corresponding text. As Hayford puts the undertow comparatively near the surface where it is conceded that it would be effective in producing folding, the existence of extensive folding is a confirmation not a contradiction of his theory of the manner in which isostatic readjustment takes place. It is certainly not fair to hold Hayford responsible, either directly or by inference, for any theory which someone else may believe which involves an undertow

[1] See p. 111 of *Special Publication No. 10*, of the Coast and Geodetic Survey.

situated entirely below the depth of compensation. Mr. Lewis apparently believes such a theory.

Second, the movements which produce isostatic readjustment are necessarily horizontal not vertical. If two adjacent columns of the same horizontal cross-section extending from the surface to the depth of compensation have different masses the readjustment to perfect compensation must involve a transfer of mass out of one column, or into the other, or from one to the other. In any case the transfer must be a horizontal movement, though it may be incidentally accompanied by a vertical movement. Hayford has already shown in print more than once that he understands that vertical movement alone does not produce isostatic readjustment. Moreover, a careful reading of his Minneapolis address will certainly show that he believes that the total amount of material moved horizontally during isostatic readjustment, and especially the total number of ton-miles of such movement, is vastly in excess of the corresponding quantities concerned in the vertical components of the movement which takes place. Hence the folding and other abundant evidence of past horizontal movements observed by geologists confirm Hayford's hypothesis as to the manner in which isostatic readjustment takes place, instead of conflicting with it as Mr. Lewis' article would lead one to think.

In contrast to the paragraph at the top of p. 623 of Mr. Lewis' article in which he claims that "the theory of isostasy does not explain the apparently heterogeneous relation of uplift and subsidence to erosion and deposition," the writer respectfully requests that certain parts of his Minneapolis address be considered in which it is set forth at some length that the movements concerned in isostatic readjustment at a given time and place are probably a function not simply of the facts at that time and place but also of the past facts there and of the current facts at many other places, some at a considerable distance, perhaps hundreds of miles away. If this be true, one should not expect to find a fixed relation of uplift and subsidence at any given point or time to the erosion or deposition in progress at that point at that time. Why does Mr. Lewis ignore this contrast?

So too, when one reads Mr. Lewis' statement (p. 623) that "in

some cases erosion to a peneplain has been followed by subsidence and in other cases by uplift" and notes that the context seems to imply that this cannot be reconciled with the theory of isostasy, one is puzzled to understand why no reference is made to that part of Hayford's address in which two long paragraphs are devoted to setting forth the errors in this particular line of reasoning.

Thus far in this rejoinder only such evidence has been cited as was available to Mr. Lewis when he wrote his article. In May, 1912, the Coast and Geodetic Survey issued a publication entitled *The Effect of Topography and Isostatic Compensation upon the Intensity of Gravity*, written by John F. Hayford and William Bowie. This contains further evidence pertinent to the questions under discussion.

In the principal computations set forth in this new publication the effects of isostatic compensation upon the intensity of gravity are computed upon the assumption that the compensation is complete and is uniformly distributed to the depth 113.7 km. The depth was adopted from the first figure of the earth investigation by Hayford and the assumption of complete compensation was retained.

Let the evidence furnished by this new publication on gravity now be considered in connection with Mr. Lewis' article.

In the new gravity publication the computations are made by concentric circular zones as in the computations of topographic deflections, but the zones are not the same. In the new publication in the table on p. 100 the effect upon gravity, at each of 41 stations in the United States, of the assumed compensation for all zones out to zone O, covering all areas within 166.7 km. of the station, is tabulated separately from the effect of the topography itself. This enables one to apply two tests as indicated below.

First, let it be assumed that for these 41 stations the compensation is only nine-tenths complete. Then the computed effect of the compensation as shown in the table should in each case be diminished by one-tenth of itself. This would produce a contrary change of the same magnitude in the anomaly, or residual, shown in the fourth column from the last in this table. An inspection of the values shows that for the 41 stations 19 residuals would be

reduced by such a change, 20 increased and two left as before. The test thus gives a neutral result.

A similar test was made on the assumption that the compensation is only one-half complete, as suggested by Mr. Lewis. Such a change would increase 29 of the 41 residuals. This is a strong indication that incompleteness of compensation does not exist to that extent.

But Mr. Lewis might say in this connection, as he did in connection with the deflections of the vertical, that an error in assuming the compensation to be complete had been offset by an error in making the depth of compensation too great. On p. 105 of the new publication there is a table showing the effect upon the computed correction for compensation of changing the assumed depth of compensation from 113.7 km. to 85.3. The ten stations in this table are also in the table on p. 100. Hence it was possible by a comparison of the two tables to compute the value which must be assigned to Mr. Lewis' quantity M, expressing the completeness of compensation, to make the assumed change in completeness at each station counteract the assumed change in depth. The comparison was made and it was found that the ten necessary values of M vary for these ten stations from .56 to 1.78, with a mean of about unity. This showed, just as it has already been shown earlier in this rejoinder, in connection with deflections of the vertical, that there is no fixed relation between the effects due to changes of assumed depth of compensation and those due to changes of assumed completeness.

Both these tests are incomplete because they utilize only a few of the 89 gravity stations and because they utilize only that portion of the compensation which is within 166.7 km. of the station. But the tests give sufficiently decisive results to show that further investigation along this line is reasonably certain to be fruitless.

The most important confirmation by the gravity publication of conclusions previously drawn from deflections of the vertical, is that shown on pp. 117–21 of the gravity publication. From studies of deflections of the vertical 11 specified areas of excessive density (under-compensation) had been located in the United

States and five specified areas of deficiency (over-compensation). The gravity observations confirm the existence of 10 of these 16 anomalous areas, there being a confirmation in every case in which the gravity stations were so located as to give a thorough test. In no case was there a contradiction between the conclusions from the gravity observations and those from observations of deflections of the vertical. If the apparent residuals in each case were due to errors in assumptions, as contended by Mr. Lewis, this confirmation could not occur. In that case the geographic distribution of the residuals would certainly be different in the two cases for the reasons indicated in the following paragraph.

The intensity of gravity at a given station is a summation of the vertical components of the gravitational forces at that point minus the centrifugal force due to the earth's rotation. The deflection of the vertical at a station dealt with in the publications criticized by Mr. Lewis depend, on the other hand, upon the summation of the horizontal components of the gravitational forces at a given point. The pendulum responds mainly to masses which are above or below it. The plumb bob responds mainly to masses which are to the right or left, before or behind the station. Hence any errors of assumption as to the distribution of the isostatic compensation necessarily produce different effects in connection with gravity computations than those same errors of assumption produce in connection with computations of the deflections of the vertical. Hence a study of the two kinds of computations for the same region furnished a very severe test for errors of assumption. It is especially important to note that if a given error of assumption produces residuals in an investigation of deflections of the vertical having a certain geographic distribution that same error of assumption would produce a different distribution of residuals in an investigation of gravity.

In the new gravity publication the computed corrections for the effects of topography and compensation are published in such detail, for every zone at every station, that Mr. Lewis or anyone else has abundant opportunity to test the effects of making the assumptions different from those upon which the computation

was based. The authors of the gravity publication feel confident that such tests, if thoroughly made, will show that the assumptions in the published computations are very near the truth.

The fact that the gravity observations confirm all the conclusions previously drawn from deflections of the vertical is an exceedingly strong indication that there are no fundamental errors in the method of computation used in either investigation.

Reviews

The Geology of the Glasgow District. By C. T. Clough, L. W. Hinxman, J. S. Grant Wilson, C. B. Crampton, W. B. Wright, E. B. Bailey, E. M. Anderson, R. G. Carruthers, with contributions by G. W. Grabham, J. S. Flett, and a chapter on the paleontology by G. W. Lee. Memoirs Geol. Survey Scotland, 1911. Pp. 270; figs. 33; pl. 1.

Sandstones and basalts are the representatives of the Old Red Sandstone period. Associated with the Lower Carboniferous limestones and sandstones are extrusives of basalt, mugearite, and tuffs and intrusives of basalt, dolerite, trachyte, felsite, trachyandesite, trachydolerite, and basaltic and trachytic tuff in vents. In Upper Carboniferous times sedimentation was predominant, although some basic sills and plugs are possibly of this age. In the Permo-Carboniferous there were intrusions of quartz dolerite sills. During the Tertiary, dikes of olivine dolerite were intruded. The Pleistocene and Recent are represented by glacial deposits, old beaches, river terraces, and flood plains.

Coal is the principal economic material and occurs in both the Upper and Lower Carboniferous. Iron carbonate and fire clays are also exploited. Many analyses of limestone are given.

A. E. F.

The Geology of East Lothian. 2d ed. By C. T. Clough, G. Barrow, C. B. Crampton, H. B. Maufe, E. B. Bailey and E. M. Anderson, with contributions by B. N. Peach and John Horne. Memoirs Geol. Survey Scotland, 1910. Pp. 226; figs. 11; pls. 12.

This educational handbook to the geology of the region discusses the formations and their faunas, and describes the associated igneous rocks. The Silurian period is represented by shales, greywackes, grits, conglomerates, and cherts. Two small granite masses, older than the Old Red Sandstone, intrude these formations. The rocks of the Lower Old Red Sandstone period consist of bosses and laccoliths of granite, porphyry, etc., and dikes of porphyrite, felsite, and lamprophyre. The

upper division of this system is represented by conglomerates, sandstones, and marls. The Early Carboniferous rocks are the Calciferous sandstone series with associated extrusives of basalt, trachydolerite, trachyte, tuffs, and ashy conglomerates and intrusives of essexite, teschenite, and analcite dolerite, monchiquite and analcite basalt. Following the Calciferous is the Carboniferous limestone series, in the middle of which is the Edge coal group, the most important strata from an economic point of view in the district. The Upper Carboniferous is represented by the Millstone grit, which is followed by but a slight representation of the true coal measures. At the close of the Paleozoic, dikes and sills of dolerite were intruded. During the Pleistocene, glaciation affected the entire region.

The petrology of the igneous rocks is thoroughly discussed, and numerous analyses are given. The economics of the area consist largely of non-metallics, of which coal is the principal product.

A. E. F.

Annual Administrative Report of the State Geologist for the Year 1910. By HENRY B. KÜMMEL.

Report on the Approximate Cost of a Canal between Bay Head and the Shrewsbury River. By HENRY B. KÜMMEL.

The Flora of the Raritan Formation. By EDWARD W. BERRY.

A Description of the Fossil Fish Remains of the Cretaceous, Eocene and Miocene Formations of New Jersey. By HENRY W. FOWLER.

The Mineral Industry of New Jersey for 1910. By HENRY B. KÜMMEL and S. PERCY JONES.

Geological Survey of New Jersey, Bulletins 1–5, 1911.

1. This bulletin recounts the operations of the Survey. A list of all publications of the present Survey is appended.

2. The sea-level canal upon which estimates were made is to be sixty feet wide with a minimum depth of six feet. Its length is 21.76 miles, a portion of which is along present waterways, and whatever excavating will have to be done will be in unconsolidated material. The estimated cost for the right of way, excavation, bridges, and disposal of material is between $2,152,404 and $2,784,887.

3. The Raritan formation is the oldest non-marine Cretaceous sediment known along the Atlantic. The paleobotanical evidence

indicates an age older than the Dakota group, and probably equivalent to the Cenomanian of Europe, and the Lower Tuscaloosa of Alabama. Part 2 of the bulletin deals with the systematic paleobotany.

4. This is a descriptive summary of the fish remains known within the limits of the state of New Jersey.

5. New Jersey ranks second in the list of states in the value of products from the clay industry. In this a decided increase is shown over the previous year. The production of iron decreased. Zinc mining had a decrease in the amount of ore hoisted, but an increase in tonnage separated. A. E. F.

The Maxville Limestone. By WILLIAM CLIFFORD MORSE. Geol. Survey of Ohio, 4th series, Bull. 13. Pp. viii+128; figs. 6; pls. 5.

The Maxville limestone is the top of the Mississippian system in Ohio, and has a thickness of about fifty feet. It is underlain by the highest member of the Waverly, and is overlain unconformably by the Sharon conglomerate, the lowest member of the Pennsylvanian. It outcrops between Zanesville and the Ohio River in two well-defined areas, separated by a region in which it is completely lacking. This bulletin adds twelve species to the Maxville fauna hitherto known. A Ste. Genevieve age is indicated with the probabilities that it corresponds to the Ohara member of that formation. In the Appalachian region the Greenbrier limestone is the equivalent in age. One chapter is devoted to abstracts of the literature on the Maxville, and one chapter to the economic uses to which the limestone can be put. Several analyses are given. A. E. F.

Wirt, Roane, and Calhoun Counties. By RAY V. HENNEN. W.Va. Geol. Survey. Pp. xx+573; figs. 6; pls. 15; maps 3.

This is one of the series of county reports being published by the Survey. It is largely descriptive and covers the history of the area, its physiography, general and detailed geology, geologic structure, oil and gas fields, coal resources, clays, road materials, building-stones, and soils. The detailed geologic contour structure map shows the location of the anticlines where the drilling for oil and gas wells would be most favorable. The soil survey of these counties is the work of W. J. Latimer and F. N. Meeker of the Department of Agriculture. The maps are on a scale of about an inch to the mile, and are in a cover separate from the text. A. E. F.

Observation on the Magdalen Islands. By JOHN M. CLARKE. N.Y. State Mus. Bull. 149, 1911. Pp. 53; pls. 17, and many unnumbered figures.

This picturesque chain of islands in the Gulf of St. Lawrence, with their romantic history of destruction to navigation crafts beginning back in the fifteenth century, and their vicissitudes of land tenure that have demoralized their development, have a simple geology. Below the sedimentaries are badly broken volcanics, associated, in part, with extensive bodies of gypseous clay. The formation of the gypsum is inferred to be due to the action of sulphur on overlying limestones. These limestones and associated shales carry a marine fauna of Mississippian age. Overlying these is a series of red sandstone of Permian age. Of peculiar interest is the presence of dreikanters in the red beds. The species from the limestone and shale fauna were found by Dr. J. W. Beebe to be largely different from the typical Mississippian fauna, a fact that calls for a basin in which to develop, separated from the Mississippi basin. The species are described and illustrated.

A. E. F.

Address Delivered at the Anniversary Meeting of the Geological Society of London. By W. W. WATTS, president of the society. *Proc. Geol. Soc. London*, Vol. LXVII (1911), 62–93.

Earth history is a history of successive geographies, and of the relation of those geographies to the living beings which successively characterized them. The geological record of any single region is a chronicle of two chief classes of events, a downward movement and uplift. The cycle of deposition is characterized, when uplift is taking place, by a thalassic or deeper water period, a deltaic or shallower period, and a terrestrial period. With resubmergence comes an estuarine period, and later still, a recurrence of thalassic conditions. The conditions in Britain during the Carboniferous period are compared to present conditions in the Gulf of Mexico region, and the British Ordovician geography finds a modern parallel in the Festoon Islands of the Pacific.

The recurrence and non-recurrence of types in cycles of deposition are discussed. Some of the effects of earth movement are seen in the metamorphism and shearing of rocks, its connection with vulcanicity and the formation of ore bodies, and its influences on life.

A. E. F.

The Younger Rock-Series of New Zealand. By P. MARSHALL, R. SPEIGHT, and C. A. COTTON. *Trans. N.Z. Inst.*, XLIII, (1910), 378–407; figs. 9; pl. 1.

Several geologists have described various unconformities in this thick series, yet no two have put them in the same stratigraphical position. Such discrepancies interested the writers to make detailed examinations of these "unconformities," the evidences for which they were unable to find. Correlation with European faunas places the lowermost of the series in the Cretaceous, the prominent limestones in the Oligocene, and the uppermost beds in the Pliocene.

A. E. F.

A Geologic Reconnaissance in Southeastern Seward Peninsula and the Norton Bay-Nulato Region, Alaska. By PHILIP S. SMITH and H. M. EAKIN. Bull. 449, U.S. Geol. Survey, 1911. Pp. 146; figs. 15; pls. 13.

The Norton Bay-Nulato region lies to the east of the southeastern portion of Seward Peninsula. Both areas were little known before this reconnaissance, for they are unimportant in connection with mining. The Nulato-Norton Bay area is largely one of Cretaceous sediments, and the southeastern portion of Seward Peninsula is part of the inclosing rim of older formations. Pre-Silurian formations are present in a highly metamorphosed condition. Less metamorphosed and lying unconformably upon the earlier are Silurian-Devonian-Carboniferous (?) strata. Intrusions and extrusions followed, accompanied by mountain-building and extensive erosion. Cretaceous formations overlie unconformably the preceding rocks, and since their deposition the region has again been subjected to diastrophism of mountain-building intensity. Intrusions followed, and later still extrusions, some of which are rather recent.

Gold placers are very local, and are only in the regions of metamorphic rocks. Gold lode mining has been attempted only in a few places, and has never gone beyond the prospecting stage. Some silver-lead mining had been done to the extent of a few hundred tons of ore. Prospecting for copper has been without success commercially. In the area of Cretaceous sediments coal is generally present, but too thin or too crushed to be of any value.

A. E. F.

Jahres-Berichte und Mitteilungen des oberrheinischen geologischen Vereines. Neue Folge, I, 1911, Hf. 2. Pp. 102; figs. 10; pls. 2; map 1.

Contains many papers by members of the society, among which the following few are of more than local importance:

"Kurze Mitteilungen über tektonische Experimente." By W. PAULCKE. Pp. 56–66; pls. 2. In these pages are given a few results of a series of experiments illustrating mountain-building forces. Strata of different degrees of hardness and subjected to considerable pressure gave, when compressed, overthrust faults, recumbent folds, thickenings and thinnings of the softer layers, and numerous other structures common to the earth's crust.

"Beitrag zur Kenntnis des Rheingletschers und der Talgeschichte der Donau von Sigmaringen bis Ulm." By DR. SCHAD. Pp. 72–92; figs. 6; map 1. Besides a description of the effects of glaciation in this valley, "hanging" drumlins are described as occurring on valley slopes, and are explained as due to the lateral push of subglacial débris up to a point where the thinner overlying ice could no longer move it and therefore overrode it.

A. E. F.

Untersuchungen über den geologischen Bau und die Trias von Aragonien. By ADOLF WURM. *Zeits. d. deuts. geol. Ges.*, LXII, 1911, Hf. 1, pp. 35–176; figs. 17; pls. 7.

Aragon lies in northeastern Spain. The Triassic system lies unconformably on the Paleozoics. It has many similarities with the Triassic of Germany, the names of whose divisions are applied to those of Aragon. The Buntersandstein has a thickness in places of more than 1,700 feet. The Muschelkalk follows with different phases in two different areas, and with a varying thickness the maximum of which is about 250 feet. The overlying Keuper is here composed largely of red and green marls and interbedded gypsum, and also has a varying thickness up to 490–650 feet. Above the Keuper is the Carñiolas, a dark-gray, fine-grained dolomite with a maximum thickness of about 250 feet. Germany has no similar formation. The paucity of fossils leaves the age of the Carñiolas uncertain. In this paper it is considered as probably equivalent to the Lower Lias. A few intrusions of "ophite" is the only representation of Triassic igneous activity. The Triassic fauna and the folded and faulted structure are described.

A. E. F.